Construction Design as a Process for Flow: Applying Lean Principles to Construction Design

by

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Submitted to the System Design and Management Program

in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management
at the
Massachusetts Institute of Technology
February 2007

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ABSTRACT

Delays and cost overruns are the rule rather than the exception in the construction industry. Design changes due to lack of constructability late in the construction phase generating costly ripple effect which create delay and disruption throughout the entire organization, are the largest contributors to the stated rule. In the building construction industry, of increased competitiveness, demand from many companies continued effort to develop new methods and tools, in which the design for quality, cost, construability and reliability play an important role.

The planning and management of building design has historically focused upon traditional methods of planning such as Critical Path Method (CPM). Little effort is made to understand the complexities of the design process; instead design managers focus on allocating work packages where the planned output is a set of deliverables. This current design method forces design teams to manage their work on a discipline basis, each working on achieving their deliverable as dictated by the design program with little regard of the relationship with other disciplines and organizations. In addition, because Architect and Engineering firms view design and construction as two separate independent phases of work in project it makes it difficult to verify constructability in a design and create flow in the overall process.

The goal of this study is to look at how aligning interests, objectives and practices based on lean fundamentals, during the earliest stages of a project, as a method of improving construction performance.

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Title: Senior Lecturer, Engineering Systems Division, Principal Researcher, Lean Aerospace Initiative

BIOGRAPHICAL NOTE

Leticia Soto is an active duty Navy Lieutenant in the Civil Engineer Corps currently working on a Masters of Science Degree in Engineering and Management. She has seven years of Military Construction Project Management experience in the US and overseas. Her last assignment was with Naval Mobile Construction Battalion Five, based in Port Hueneme, Ca. During her tour there she spent time in Okinawa, Japan, Balad, Iraq and Ali Al Salem, Kuwait managing contingency construction projects.

Lieutenant Soto is a graduate of the Basic Navy Civil Engineer Corps Course. She is Seabee Combat Warfare qualified and her personal awards include Army Commendation, Navy Commendation with two gold stars, Navy Achievement Medal with three gold stars, Navy Unit Commendation and Meritorious Unit Commendation, and other campaign service awards.

Lieutenant Soto graduated in 2000 from Purdue University with a Bachelor of Science in Electrical Engineering and this work completes requirements for her Masters of Science in Engineering and Management from the Systems Design and Management Program at the Massachusetts Institute of Technology.

ACKNOWLEDGEMENTS

Boston, Massachusetts Leticia Soto

January 10, 2007

I would like to thank Dr. Donna Rhodes, my supervisor, for her patience, insight and constant guidance during this research. It has been a pleasure to have her as a mentor.

Additionally, Dr. Gregory Howell, co-founder of the Lean Construction Institute, for providing me with outstanding research material and insight. DPR Construction for providing me information on their experiences applying Lean Construction methodologies and Building Information Modeling.

SDM '06 classmate Major Nathan Minami for helping me immensely by providing continual guidance on various aspects of my thesis. The numerous hours he dedicated to mentoring and teaching me the complexities of System Dynamics were invaluable. His commentary was vital to the completion of my thesis.

Lastly, and most importantly, I am grateful for the continuous love and support of my family; my wonderful mother Maria, and my two daughters Esabel and Maritza. They are my drive to succeed.

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Part I – BACKGROUND/LITERATURE REVIEW

CHAPTER 1: Introduction

Problems in construction are recognized by many and impact more than the immediate. The productivity in construction leaves nothing to be envied; occupational safety is notoriously worse than in any other industry; quality in construction needs to be continually monitored; and the inferior working conditions cause work force shortages. Numerous solutions have been offered to help the many chronic problems in the construction industry, but to date none have been very effective. All efforts to improve the above mentioned conditions have been largely done at the construction site and project management level. Very little has been done to find ways to improve the design process that has the largest impact on how the project will unfold.

Manufacturing has been a source of innovations in construction for many decades. For example, the idea of industrialization comes directly from manufacturing. In addition, computer integration and automation also have their origin in manufacturing, where their implementation is well ahead compared to construction. Therefore, looking to lean practices originating in manufacturing offers potential for further improving construction.

The study on which this paper is based consisted mainly of a literature review and a conceptual analysis and synthesis. In the last stage of this study a system dynamics model was developed to better understand the dynamic impact that occurs during the design process.

Section 1.1 - Define Concern/Question

The view of a construction project based on flow process leads to theoretical understanding and to practical guidelines for improvement. Theoretically, the causes for the chronic problems in construction are clarified by pinpointing the generic process problems from which they originate. The problems of construction fall into two different clusters of causes. The first is the application of traditional design, production and organization concepts, which in the course of time have become inefficient. Secondly, construction has peculiarities which have not been adequately handled. These issues necessitate special consideration in regard to avoiding or alleviating their detrimental impact on process control and improvement. This study will show how the incorporation of lean principles and thinking to construction design will enable process flow and control. Furthermore an organizational framework which encourages and supports process flow.

Section 1.2 - Define Scope/Goal

The primary goal of this paper is to develop a systems process which integrates lean principles enabling project design to be conducted in a way that avoids, reduces, or mitigates variability during the construction process in order to facilitate flow. The owner or facility sponsor of a construction project holds the key to influence construction costs of a project because any decision made at the beginning stage of a project life cycle has far greater influence than those made at later stages, as shown in Figure 1-1. Moreover, the design decisions will influence the continuing operation costs and, in most cases, the revenues over the facility lifetime. This study will show this common knowledge that when the correct changes are made early in the design development the impacts to cost and schedule are minimal. A secondary goal is to provide a conceptual framework on which a project can be modeled to ensure proper collaboration between the designer and construction contractor and sub contractors during the design process. Specifically it will address the question of "can manufacturing principles of production be effectively applied to the construction industry", and recommend how part of the construction cultural change can be handled to empower contractors.

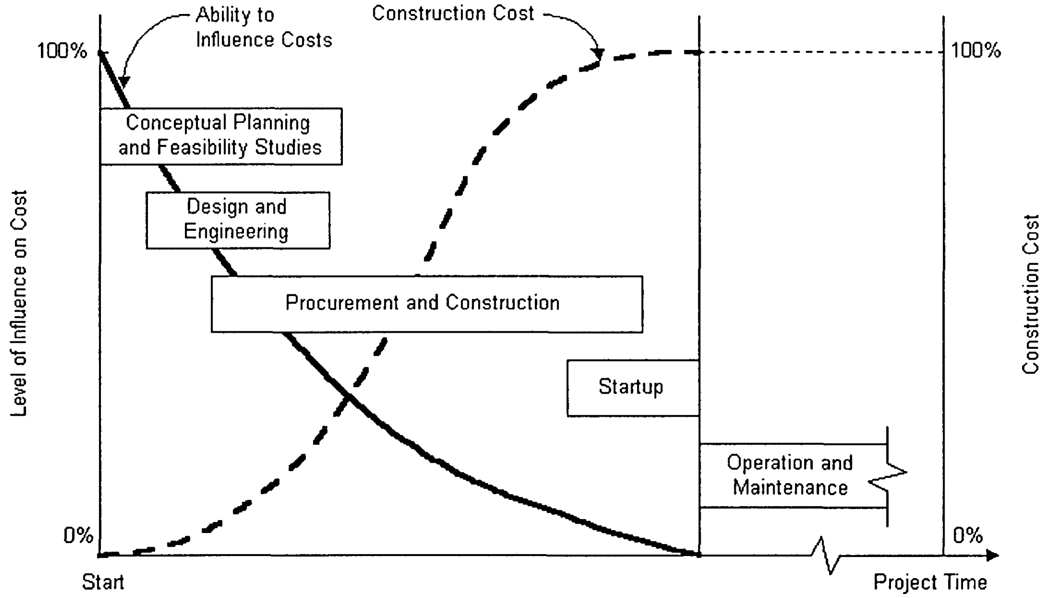

Figure 1-1 Ability to Influence Cost over Time [1]

Section 1.3 - Project Description/ Method

This thesis will look at how manufacturing practices of production can be applied to construction design to create flow. It is divided into three parts, Part I Literature Review, Part II Analysis of Current Design Process and Part III Lean Thinking Applied to Construction Design.

The current state of the construction industry and common practices of construction methodologies continually fall short of customer value expectations. The literature review will start with exploring Lean Principles and Thinking and the successes in Lean Production. Next it will address the current construction environment. This will allow for a good foundation to review how the peculiarities in construction, construction management and contractual relationships in construction design inhibit flow After which a brief view of how computer integrated construction and building information modeling techniques support lean thinking in design is presented. Lastly, an introduction to the development of the Lean Construction Institute, their developments in applying lean to

[1] Hendrickson, Chris, Project Management for Construction, 2000, Prentice Hall, Pittsburgh, PA, p 15

the construction industry, and a review of projects utilizing their theories will be presented.

Part II, Analysis of Current Design Process, will start with a critique of the flow process in construction design. Next, System Dynamics will be utilized as a tool to examine construction design errors and develop an organizational architecture to avoid root causes of design errors. Lastly, highlights of design optimization alternatives to reduce negative iteration will be presented.

Finally, a framework of recommendations and conclusions, based on the findings from this study will be presented, which will allow for construction design as a process for flow.

CHAPTER 2- Lean Concepts

Section 2.1- Lean Thinking

Lean thinking got its name from a 1990's best seller called *The Machine That Changed the World : The Story of Lean Production*[2]. This book chronicles the movement of automobile manufacturing from craft production to mass production to lean production. It tells the story of how Henry Ford standardized automobile parts and assembly techniques, so that low skilled workers and specialized machines could make cheap cars for the masses. The book goes on to describe how mass production provided cheaper cars than the craft production, but resulted an explosion of indirect labor: production planning, engineering, and management. Then the book explains how a small company set its sights set on manufacturing cars for Japan, but it could not afford the enormous investment in single purpose machines that seemed to be required. James P. Womack, and Daniel T. Jones further distilled lean thinking into five principles in their book, Lean Thinking, which are:

- Specify the value desired by the customer
- Identify the value stream for each product providing that value and challenge all of the wasted steps (generally nine out of ten) currently necessary to provide it
- Make the product flow continuously through the remaining, value-added steps
- Introduce pull between all steps where continuous flow is possible
- Manage toward perfection so that the number of steps and the amount of time and information needed to serve the customer continually falls

In the subsequent sections of this chapter a brief overview of what these principles mean and how they have been applied will be presented.

Section 2.1.1 – Value

The first and most critical lean principle as presented in Lean Thinking is Value. Womack and Jones emphasize that value can only be defined by the ultimate customer

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[2] The Machine That Changed the World: The Story of Lean Production, by Womack, James P.,Daniel T.Jones and Daniel Roos, New York: Rawson and Associates; 1990

and it's only meaningful when it is expressed in terms of a specific product (a good, or a service, and often both at once) which meets the customer's needs at a specific price at a specific time.[3] Finding methods to capture customer-driven value is not a new activity. Most organizations have probably analyzed processes, conducted customer surveys, and used audit to determine what customers want. Yet these techniques are not enough. Overall the stated techniques still departmentalize the value concept. A more holistic view of value that stretches beyond organizational boundaries and streams from manufacturer to supplier to producer with an analysis of time and cost is most effective in defining value.

In Value, "It's Measurement, Design and Management," the authors, M. Larry Shillito and David J. DeMarle, make a strong case that value is a function of time. [4] This is consistent with the Lean Thinking inclusion of "at a specific time". The timing of when a product reaches market has a strong influence over the perceived value of the product. One can associate this with the value you get from the measurement against perfection seems to be the most appropriate when focused on the "Price" portion of the value equation. A company should strive to eliminate all muda (waste) and thus achieve the "ideal" cost of producing a give product or service. Cost should be considered in all aspects from the lifecycle perspective, the cost to retire the product and maintain. Since the "ideal" is based on non-price attributes, such as "Quality", value must be defined with a specific product with specific capabilities offered at specific prices.

Section 2.1.2 – The Value Stream

The most effective process is achieved by performing the minimum number of value-added steps and no non –value added steps. The method to maximize value-added steps in lean practice is through value stream mapping. The value stream is "specific activities required to design, order and provide a specific product from concept to launch, order to delivery, raw material into the hands of the customer."[5]

[3] Womack and Jones, Lean Thinking, 16
[4] M. Larry Shillito and David J DeMarle, Value: Its Measurement, Design and Management (New York Jonh Wiley & Sons, Inc., 1992) 11-14
[5] Womack and Jones, Lean Thinking , 311

Performing a value stream analysis distinguishes three types of activities: (1) activities which unambiguously create value, (2) activities which create not value but are unavailable with current technologies and production assets, and (3) activities which create no value and can be eliminated immediately. Activity (3) should be eliminated, and activity (1) and (2) will be examined to improve the activity and to eliminate waste from them.

Section 2.1.3 – Flow

The third principle is flow, once all the wasteful activities are eliminated the remaining value-creating steps need to 'flow'. Conceptually companies have a difficult time applying beyond internal departments. True integration of functions and departs in a company into product teams organized along the value stream enable and promote flow of information and materials.

Section 2.1.4 – Pull

Pull is defined as "a system of cascading production and delivery instructions from downstream to upstream activities in which nothing is produce by the upstream supplier until the downstream customer signals a need".[6] The following three characteristics are necessary conditions for pull.

Synchronization (Timing)

Synchronization refers to aligning takt times of interconnected process such that proper timing is in place, thus enabling flow and allowing for pull to be successful.

Alignment (Position)

Alignment describes proper positioning that is necessary for pull to occur. In a manufacturing sense this could mean physical position, in a development point of view this could mean proper file format and location.

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[6] Womack and Jones, Lean Thinking, 311

Transparency

Transparency describes the ability to see the process totally and without obstruction as a means for identifying problems quickly and efficiently.

Section 2.1.5 – Perfection

Perfection is the continuous improvement aspect of Lean. Understanding that a process today is imperfect and that there is a need for continuous reexamination of the process/product is necessary to remain competitive and lean.

Section 2.2 - Lean Production

The purpose of this section is to review lean production control theory and practice as it may apply in construction.

Section 2.2.1 – Lean Production History

Lean production has its origin in the Toyota Production System in Toyota Motor Company. Lean production is a completely different concept from mass production. Before the lean production system, mass production dominated the manufacturing industry. When Toyota made a strategic decision to pursue a different production system after World War II, automobile companies in the United States and European countries were already large and enjoyed the economies of scale of the mass production system. Toyota could not follow the mass production system because the Japanese domestic automobile market was small and fragmented, the workforce was in short supply, natural sources were scarce, land was limited and little capital was available for investment. To overcome these constraints, Toyota developed a productions system that used less of everything compared with mass production- less human error in the factory, less manufacturing space, less investment in tools, and fewer engineering hours to develop a new product.

At first, the Toyota Production System did not attract other Japanese manufacturing companies' interest because their business went well during the era of high speed economic growth. However, after the energy crisis in 1973, economic growth slowed down and the companies no longer prospered using mass production. Then Japanese manufacturing companies started to express considerable interests in the Toyota Production System (TPS).

Section 2.2.2 – What is Production?

Production is a topic that has been most closely studied primarily in industrial engineering, which has dealt almost entirely with one type of production; namely , manufacturing, with only occasional use in construction, plant maintenance, building maintenance, agriculture etc. Design and engineering have infrequently been conceived as production process; the focus almost entirely is being placed on making things rather than designing them.[7]

Being able to define production as the designing and making of product allows us to understand how construction is a type of production and also that design is an essential component in production and in construction specifically.

Section 2.2.3 – What is Production Control?

The essential activity of production control is monitoring actual costs or schedule performance against target in order to identify negative variances. Corrective action is obviously necessary in order to correct such negative variances.

Production control theorists working in manufacturing distinguish two primary ways of regulating work flow in manufacturing systems: push and pull. Push systems release material or information into a system based on a preassigned due dates. Pull systems release materials or information into a system based on the state of the system in addition to due dates. In factory systems, pull is ultimately derivative ultimately from customer orders. In construction, pull is ultimately derivative from target completion dates, but specifically applies to the internal customer of each process.

Just in Time- JIT

JIT applies primarily to a repetitive process in which the same product and components are produced over and over aging. The general idea is to establish flow processes (even

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[7] Ballard, The Last Planner System of Production Control, 2-1

when the facility uses a jobbing or batch process layout) by linking work centers so that there is an even, balanced flow of materials throughout the entire production process, similar to that found in an assembly line. To accomplish this, an attempt is made to reach the goals of driving all inventory buffers toward zero and achieving the ideal lot size of one unit.

Total Quality Control (TQC)

The quality movement in Japan has evolved from mere inspection of products to total quality control. The term total refers to three extensions: 1) expanding quality control from production to all departments, 2) expanding quality control from workers to management, and 2) expanding the notion of quality to cover all operation in the company. [8]

Quality methodologies have developed in correspondence with the evolution of concept of quality. The focus has changed from an inspection orientation (sampling theory), through process control (statistical process control and the seven tools), to continuous process improvement and presently to designing quality into the product and process (Quality Function Development).

[8] Shingo Shigeo. 1988. Non-stock production. Productivity Press, Cambridge, MA p454.

CHAPTER 3-Current Design in Construction

"The definition of insanity is doing the same thing over and over again and expecting different results"

Albert Einstein

Section 3.1 – Construction Environnent Today

There are many undesirable characteristics of current construction with difficulty in defining or measuring values, poor integration, inability to design to set budget and missed opportunity for adding and capitalizing on value. In this section an overview of the construction industry will be presented.

Section 3.1.1 – Project Life Cycle

The acquisition of a constructed facility usually represents a major capital investment, whether its owner happens to be an individual, a private corporation or a public agency. Since the commitment of resources for such an investment is motivated by market demands or perceived needs, the facility is expected to satisfy certain objectives within the constraints specified by the owner and relevant regulations. With the exception of the speculative housing market, where the residential units may be sold as built by the real estate developer, most constructed facilities are custom made in consultation with the owners. A real estate developer may be regarded as the sponsor of building projects, as much as a government agency may be the sponsor of a public project and turns it over to another government unit upon its completion.

From the perspective of an owner, the project life cycle for a constructed facility may be illustrated schematically in Figure 3-1. Essentially, a project is conceived to meet market demands or needs in a timely fashion. Various possibilities may be considered in the conceptual planning stage, and the technological and economic feasibility of each alternative will be assessed and compared in order to select the best possible project. The financing schemes for the proposed alternatives must also be examined, and the project will be programmed with respect to the timing for its completion and for available cash flows. After the scope of the project is clearly defined, detailed engineering design will provide the blueprint for construction, and the definitive cost estimate will serve as the baseline for cost control. In the procurement and construction stage, the delivery of materials and the erection of the project on site must be carefully planned and controlled. After the construction is completed, there is usually a brief period of start-up or shake-down of the constructed facility when it is first occupied. Finally, the management of the facility is turned over to the owner for full occupancy until the facility lives out its useful life and is designated for demolition or conversion.

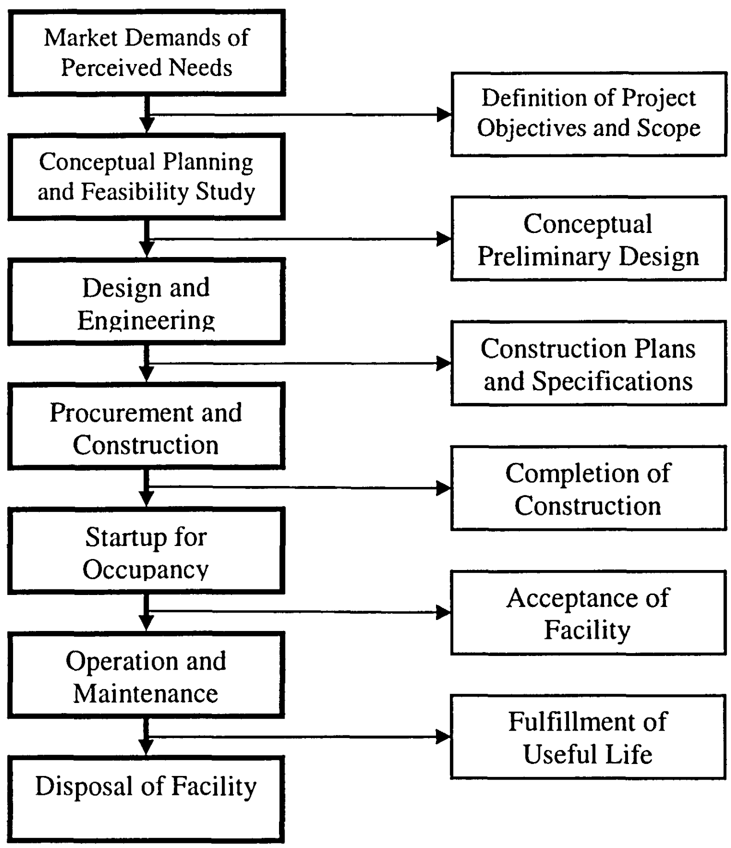

Figure 3-1 Project Life Cycle of a Constructed Facility

Of course, the stages of development in Figure 3-1 may not be strictly sequential. Some of the stages require iteration, and others may be carried out in parallel or with overlapping time frames, depending on the nature, size and urgency of the project. Furthermore, an owner may have in-house capacities to handle the work in every stage of the entire process, or it may seek professional advice and services for the work in all stages. Understandably, most owners choose to handle some of the work in-house and to contract outside professional services for other components of the work as needed.

Section 3.1.2 – Delivery Methods

In recent years, the construction industry has developed new innovative delivery methods beyond the more traditional of only assembly part of the business. Typically the conditions and timing greatly impact the delivery; below are the four most common delivery methods.

General Contract (GC) The traditional method by which the client defines a design with the help of an engineering or architecture firm, bids and awards it for construction. The construction company that wins then builds according to the design requirements. 100% of the design is completed when construction companies bid for the job. This is the traditional method.

Design-Build (DB) The client awards both the design and the construction to the same company. The construction company designs and builds based on some general specs but it has a lot of freedom with the detailed design. Normally only the conceptual design is finished at the time of bid.

Turnkey (T) The client awards both the design and the construction to the same company and the company doesn't get paid until the project is finished. This method is quite similar to DB but it involves some sort of long term financing. Only infrastructures capable of generating revenue can use this delivery method.

Build Operate Transfer (BOT) The client awards the design, construction and the legal right to operate the infrastructure for a number of years to the same company. The company is paid by collecting revenues from the operation. This method is quite similar to DB but it involves some sort of long term financing. Only infrastructures capable of generating revenue can use this delivery method.

Section 3.2 – Design in Construction Process

It is important to recognize the close relationship between design and construction. These processes can be viewed as an integrated system. Broadly speaking, design is the process of creating the description of a new facility, usually represented by detailed plans and specifications; construction planning is a process of identifying activities and resources required to make the design a physical reality. Hence, construction is the implementation of a design envisioned by architects and engineers. In both design and construction, numerous operational tasks must be performed with a variety of precedence and other relationships among the different tasks. In this section a review of the two most common construction design processes will be presented.

Section 3.2.1 – Sequential Design in Construction

In sequential design and engineering, the total task is divided into temporary sequential tasks, which are given to different specialist for execution. This has been the conventional method of organizing product development in manufacturing. In construction, the traditional approach to a project is similar. Here, the client first selects an architect, who prepares overall designs and specifications. Designs for structural and mechanical disciplines are then prepared. Construction is the responsibility of a general contractor under contract to the client.

The problems of the traditional, sequential approach to construction have been widely discussed in recent years. However, what has not been generally realized is that this procedure leads to several generic flow process problems. Below are some of the most common problems encountered[9].

- Constraints of subsequent phases are not taken into account in the design phase (poor consideration of requirements of next internal customers)
- Unnecessary constraints for subsequent phases are set in the design phase (poor consideration of requirements of next internal customers)
- Little feedback for specialist (poor process transparency, segmented project control)

[9] Dupagene, A. (ed). 1991. Computer Integrated Building. Strategic Final Report. ESPRIT II: Exploratory Action No 5604. December 1991.

- Lack of leadership and responsibility for the total project (segment project control).

Consequentially, the sequential procedure leads to the following:

- Suboptimal solutions
- Poor construability and operability.
- Large number of change orders
- Lack of innovation and improvement.

As noted above there is definite room for improvement for the traditional design process.

Section 3.2.2 – Integrated System Design in Construction

In an integrated system, the planning for both design and construction can proceed almost simultaneously, examining various alternatives which are desirable from both viewpoints and thus eliminating the necessity of extensive revisions under the pretext of value engineering. Furthermore, the review of designs with regard to their constructability can be carried out as the project progresses from planning to design. For example, if the sequence of assembly of a structure and the critical loadings on the partially assembled structure during construction are carefully considered as a part of the overall structural design, the impacts of the design on construction false work and on assembly details can be anticipated. However, if the design professionals are expected to assume such responsibilities, they must be rewarded for sharing the risks as well as for undertaking these additional tasks. Similarly, when construction contractors are expected to take over the responsibilities of engineers, such as devising a very elaborate scheme to erect an unconventional structure, they too must be rewarded accordingly.

While the conceptual design process may be formal or informal, it can be characterized by a series of actions: formulation, analysis, search, decision, specification, and modification. However, at the early stage in the development of a new project, these actions are highly interactive as illustrated in Figure 3-2. Many iterations of redesign are expected to refine the functional requirements, design concepts and financial constraints, even though the analytic tools applied to the solution of the problem at this stage may be very crude.

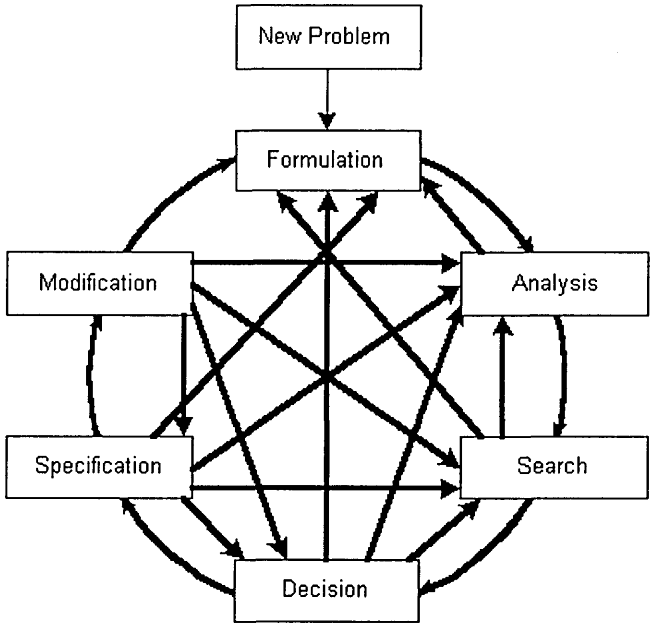

Figure 3-2 Conceptual Design Process [10]

The series of actions taken in the conceptual design process may be described as follows:

Formulation- refers to the definition or description of a design problem in broad terms through the synthesis of ideas describing alternative facilities.

Analysis- refines the problem definition or description by separating important from peripheral information and by pulling together the essential detail. Interpretation and prediction are usually required as part of the analysis.

Search - involves gathering a set of potential solutions for performing the specified functions and satisfying the user requirements.

Decision -means that each of the potential solutions is evaluated and compared to the alternatives until the best solution is obtained.

Specification- is to describe the chosen solution in a form which contains enough detail for implementation.

[10] R.W. Jensen and C.C. Tonies, *Software Engineering*, Prentice Hall, Englewood Cliffs, NJ, 1979, p.22

Modification -refers to the change in the solution or re-design if the solution is found to be wanting or if new information is discovered in the process of design.

As the project moves from conceptual planning to detailed design, the design process becomes more formal. In general, the actions of formulation, analysis, search, decision, specification and modification still hold, but they represent specific steps with less random interactions in detailed design. The design methodology thus formalized can be applied to a variety of design problems.

Section 3.3 – Major Problems in Construction Flow

There are two main processes in a construction project, design process and construction process. The design process is a stage wise refinement of specifications where vague needs and wishes are transformed into requirements then via a vary number of steps to detailed design. Simultaneously, this is a process of problem detection and solving. The construction process is composed of two different types of flows, material and work process. Material process consisting of the flow of material to the site and work processes of construction team.

The most acute flow problems of construction design are caused either by traditional design, production and organization concepts, or the peculiarities of construction. In this section five major problems in construction that prevent flow will be presented, with an emphasis on the design process.

Section 3.3.1 – Peculiarities in Construction

Because of its peculiarities, the construction industry is often seen in a class of its own, different from manufacturing. These peculiarities are often presented as reasons or excuses when well established and useful procedures from manufacturing are not implemented in construction.

Other construction attributes, such as durability and costliness, are not considered relevant in the context. Also construction may be characterized as complex and uncertain.

These two features, which are shared by many other industries, are treated as resultant process features rather than primary peculiarities. Construction peculiarities refer especially to following features[11]:

One-of- a kind nature of products

The one –of-a kind nature of each building or facility is caused by differing needs and priorities of the client, by differing sites and surroundings, and by differing views of designers on the best design solutions. This one-of-a-kind nature, which varies along a continuum, covers most often the overall form of the building or facility. From the point of view of contractors and design offices, there is continuity and repetition: roughly similar projects and tasks recur[12]. Thus it has to be stressed that the problems associated with one-of-kindness affect only certain processes in any project.

Usually there is significant input into the design process by the client, who is often a one-time participant in the process and thus does not have the benefit of learning from prior project cycles.

Site production

Construction production is typically carried out at the final site of the constructed product, often inside the evolving product. Although this peculiarity has significant impacts on the construction of a facility, it will not be covered in detail because of it's minimal impact on design. A general comment for site production is that because the working environment is continuously evolving, spatial flow of work is difficult.

Temporary multi-organization

A construction project organization is usually a temporary organization designed and assembled for the purpose of the particular project. It is made up by different companies and practices, which have not necessarily worked together before, and which are tied to

[11] Warszawski, A. 1990. Industrialization and Robotics in Building: A Managerial Approach. Harper & Row, New York p 466.
[12] Plossl, George W. 1991. Managing in the New World of Manufacturing. Prentice Hall, Englewood Cliffs. P 187.

the project by means of varying contractual arrangement. This is a multi organization. Its temporary nature extends to the workforce, which may be employed for a particular project rather than permanently.

The problems for process control and improvement are related to the principles concerning continuous improvement, variability and complete process as the focus of control. In practice there are problems of:

- Communicating data, knowledge and design solutions across organizational borders stimulating and accumulating improvement in processes which cross organizational borders
- Achieving goal congruity across project organization
- Stimulating and accumulating improvement inside an organization with a transient workforce.

Regulatory intervention

The design solution and many work phases in construction project are subject to checking and approval by regulatory authorities. Authority intervention causes uncertainty and constraints to the process. Getting an approval for a design solution is often unpredictable. Checking by authorities during the construction process can cause delays. Codes may be barriers for innovation if they rigidly require a procedure, rather than a performance.

Section 3.3.2 – Flow Problems in Construction Management

Generic managerial concepts, CPM (Critical Path Method) network methods are a specific problem source in construction. These managerial principles violate principles of flow process design and improvement and thus lead to non-optimal flows and an expansion of non value adding activities.

The flaw of these methods has been observed to varying degrees and alternatives have been sought, with insufficient sound theory and have failed. The conventional managerial concepts maybe structured in three groups: sequential method of project realization, which was presented in a previous section, lack of quality considerations, which will be presented in the next section and segmented control.

Segmented control

In the conventional approach, parts of a flow process are controlled rather than the whole. More often than not, the reason for this is the hierarchical organization.

Control in a hierarchical organization focuses on an organizational unit or task, the costs of which are to be minimized. This leads to maximization of utilization and to large batches. This mode of control is characterized by both accumulation of the work-in-process between units or operations and disruptions due to material or information shortages. The situation is further aggravated by specialization which leads to an increase in number of units or tasks.

Section 3.3.3 - Waste and Value Loss in Construction Design

Since flow aspects in construction have been neglected it is logical that current construction would demonstrate a significant amount of waste, loss of value and non value added activities.

Quality costs are perhaps the best research area of waste. In numerous studies from different countries, the cost of poor quality (non conformance), as measured on site, has turned out to be 10-20% of total project costs.[13] In an American study of several industrial projects, deviation costs averaged 12.4% of the total installed project costs, however, "this value is only the tip of the iceberg".[14]

The causes of these quality problems are attributed to

- design 78%
- construction 17%
- material supply 5%

[13] Cnuddle, M. 1991. Lack of quality in construction – economic losses, European Symposium on Management, Proceedings, pp. 508-515.

[14] Burati, James L., Mathews, Michael F. & Kalidindi, S.N. 1991. Quality Management in Construction Industry. Journal of construction Engineering and Management, Vol 117, No.2, pp 341-359

Thus, quality problems are considerable in all phases of construction. Especially design is often the source of quality problems: sometimes it seems that the wastes and losses cause by design are larger than the cost of design itself. Even if there is a lack of data on the internal waste in design, it can be inferred that a substantial share of design time is consumed by redoing or waiting for information and instructions.

Constructability is the capability of a design to be constructed (The Construction Management Committee 1991). Constructability of a design depends on the consideration of construction constraints and possibilities. Projects were construability has been specifically addresses have reported 6 – 10% savings of construction costs.[15]

Section 3.3.4 - Contractual Relationships in Design

Maximizing value and minimizing waste at the project level is difficult when the contractual structures inhibits coordination, stifle cooperation and innovation, and rewards individual contractors for both reserving good ideas, and optimizing their performance at the expense of others. What was wrong? What was standing in the way of their being able to work as a true team; one able to work together to maximize value while minimizing waste throughout the process?

In the pursuit of answers to these questions, a consortium of design professional and construction practitioners met for five years to determine if there might not be a better way to organize themselves to deliver a project then their current model.[16] Their research has led them to four major systemic problems with the traditional contractual approach. The four problems with a brief explanation are as follows:

Problem 1: Good ideas are held back

The Mechanical, Electrical and Pluming contractor and other major trades were generally brought into the process by the GC once the drawings were at the design development stage in order to establish a competitive price. Even though the trades were frequently consulted through the design process, there was no real commitment to or from them

[15] Constructability, a Primer. 1986. CII Publication 3-1

[16] Matthews, Owen and Howell, Gregory, Integrated Project Delivery An Example of Relational Contracting, Lean Construction Journal 2005, p 46-61.

because the number of different companies representing the same trades were involved. As a result, each of the trade contractors saved their best ideas in hopes of gaining a competitive edge during the "bidding process." Many times these ideas were very good. Time and opportunity for innovation among were lost as the design team attempted to revamp their designs to accommodate the best of these late arriving ideas.

Problem 2: Contracting limits cooperation and innovation

A systemic, but less obvious problem was the system of subcontracts that link the trades and form the framework for the relationships on the project. The price contactor held the contract for every consultant and subcontractor. Long and tedious subcontract agreements attempted to spell out in great detail exactly what each subcontractor was to provide, rules for compensation, and sometimes useful, if unrealistic, information about when work was to be performed. These long subcontracts mostly dealt with remedies and penalties for non compliance. These contracts made it difficult to innovate across trade boundaries even though the work itself was frequently interdependent.

Problem 3: Inability to coordinate

While some project held "partnering" sessions, there was no formal effort to link the planning systems of the various subcontractors, or to form any mutual commitment or expectations amongst them.

Problem 4: The pressure for local optimization

Each subcontractor fights to optimize his performance because no one else will take care of him. The subcontractor agreement and the inability to coordinate drive subcontractors to defend their turf at the expense of both the client and other subcontractors. Traditional subcontracting agreements make subcontractors take a legalistic and litigious stance making optimization impossible.

During their research a new process which they called Integrated Project Delivery (IPD) was taking shape. Primary Team Members would include the Architect, key technical consultant as well as general contractor and key subcontractors.

Their team determined that the relationships would be between the Team Member that holds the prime contract with the client and between the Team Member and the other Primary Team Members (PTM).

Each PTM, including the one who holds the prime contract enters into a single "pact" with the other PTMs. They each jointly and severally bind themselves to each other and to the fulfillment of all the terms, conditions and requirements of the prime contract. Further, PTMs agree in this "pact: to share the cost on the project and to distribute profit based upon a formula that rewards the PTMs in accordance with their participation on the project. The entity that signed the Prime contract is simply a PTM and receives profit based on the same formula and in this same manner as the other PTMs.

Key Pact provisions:

- The PTMs each agree to be bound together accepting full responsibility for all the terms and conditions of the prime contract, sharing together in the cost and profit in accordance with the pre-established formula.
- Each of the PTM's provides a certificate of insurance in the form and amounts as indicated in the prime contract.
- Each PTM agrees to open their books pertaining to this project to the other PTMS and to the Client.

The findings from their research found that the ideal contractual relationship would be one that incorporated transactional and relational contracts. Transactional contracts where exchanges are made for goods and services and Relational contracts where the relationship takes on the properties of a mini-society with a vast array of norms beyond those centered on the exchange and its immediate processes.

The IPD employs both the transactional and relational contracts. Externally they enter a classic transactional contract with the client and some suppliers. Internally, members are bound by a relational contract described in the "pact" they all sign. The "pact" minimizes transactional cost by binding the parties together in a partnership for the duration of the project. Records are not kept to allocate costs or determine blame. Currently there are many firms that have adopted the IPD with success, but there is no doubt that the largest obstacle is the cultural change in the relationship between all the subcontractors and the general contractor.

Section 3.3.5 – Negative Iteration

Assuming that design by nature is an iterative and generative process, how do we distinguish from negative iteration? Waste is characterized in terms of minimizing what is unnecessary for task completion and value generation. Consequently, that iteration is wasteful which can be eliminated without loss of value or causing failure to complete the project. Informal surveys of design team have revealed estimates as high as 50% of design time spent on needles iteration[17]. There are many contributors to the negative iteration, but it would be best to start by addressing the sequence of design tasks. Design Structure Matrix (DSM) is a device for elimination or reducing loops by re-sequencing design tasks. That seems simple enough, so there must be more to the cause of negative iteration.

The willingness to share incomplete information has long been identified as a necessity for concurrency in design.[18] This can perhaps be best understood in terms of the lean production practice of reducing batch sizes, which belongs with DSM as a technique for restructuring the design process.

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[17] Koskela, L. & Huvolia, P (1997). "On Foundations of Concurrent Engineering" in Anumba,C. and Evbuomwan, N (eds). Concurrent Engineering in Construction CEC91. London 3-4 July.
[18] Clark, Kim B. & Fujimoto, T (1991). Product Development Performance, Harvard Business Press, Cambridge, MA.

CHAPTER 4- Computer Integrated Construction

Section 4.1 – Building Information Modeling

A Building Information Model (BIM) is a digital representation of physical and functional characteristics of a facility. BIM is historically linked to 3D and now 4D virtual modeling of buildings, though it has the capability to be much more. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward. A basic premise of BIM is collaboration by different stakeholders at different phase of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of the stakeholder. BIM is shared digital representation founded on open standards for interoperability. Figure 4-1 demonstrates how building information over time becomes the facility information backbone; during the owner operations phases. For the purposes of this study we will concentrate on the benefits that BIM provides during the design phase. Although BIM is very much like a 3 and 4 D CAD tool the value is in the additional information that the graphic representation can support.

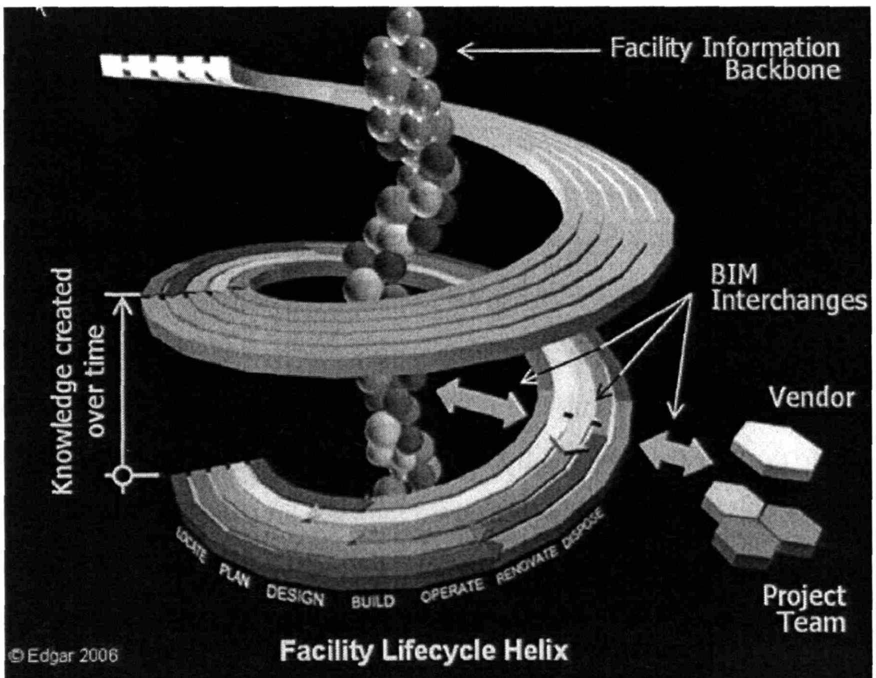

Figure 4-1 BIM Facility Lifecycle Helix [19]

[19] Edgar, Alan, Right Thinking About BIM and The National BIM Standards Committee, http://www.aecbytes.com/buildingthefuture/2006/BIMstandards.html

Section 4.1.1 – BIM and Lean Working Together

An example of where BIM and Lean practices were utilized together is the Flint project, a 442,000 sq ft addition to a Global V6 engine plant for General Motor. GHAFARI was the A/E of record and the BIM integrator for the design/build team, working in collaboration with the lead contractor, The Ideal Contracting Inc. They were presented with the challenge to design and deliver this manufacturing facility under an extremely fast-tracked schedule of less than 40 weeks, while keeping the costs under control and maintaining the highest standards of quality and safety during construction. A comparable fast track design/bid/build could have required approximately 60 weeks from design to project closeout, while a fast track conventional design/build approach would have required approximately 50 weeks. To meet the schedule and cost requirements, one of the most critical requirements was that of ordering the 4500 tons of steel from the mill in less than 3 weeks from the start of design, as opposed to the normal time frame of 8-14 weeks. If the steel mill order could not be issued within the required 3 weeks, the mill rolling cycle would have been missed and the team would have been forced to order steel from the warehouses, significantly increasing cost.

The owner and design/build team agreed from the start of the project to use 3D BIM during design and constructions, as they knew that is could not be delivered on schedule and within budget if the team was to use conventional delivery systems and methodologies. The design team created 3D BIM models for all discipline including architectural, structural, HVAC, plumbing, fire protection and electrical. The entire design was fully coordinated using the 3D models, after which the 2D documentation was extracted from them. Both the fully coordinated 3D models and the associated 2D documents were then released to the sub-contractors, who used the 3D models to produce installation drawings and in some cases, to also drive their fabrication equipment. Even after the ownership of the models was transitioned to the sub-contractors the design team continued to review the install level models with the sub-contractors until all issues were resolved prior to construction. Because of the process and the commitment from the installing contractors to build-to-the-model, there were zero changed due to design conflicts during the construction of the project.

Important as 3D BIM was to the success of this project, also critical were factors such as advanced planning, supply chain project management, and team commitment to apply lean principles. GHAFARI created a dedicated advanced technologies group for the project that took the lead in applying lean construction principles and 3D enabled delivery for eliminating wasteful practices especially at handoffs between design, detailing, fabrication, and installation phases. A lean concept called "Kaizen Bursts" was used at various stages of the project to streamline workflow. Kaizen Bursts are short and focused sessions that include value stream mapping, analysis, and workflow re-engineering aimed at eliminating non-value adding activities. Collaboration was also greatly enhanced by key members of the design/build team including the A/E, sub-contractors, and the owner's engineering team co-locating at the offices of the General Contractor for approximately 3 months. At this co-location center, the design/build team worked closely to clarify project objectives, define scope and fully coordinate the design prior to construction. As design decisions were being made, they were incorporated in the BIM models and reviewed for cost and constructability. Subsequently, all coordination and collaboration activities proceeded with weekly on-board review of the 3D model instead of the traditional 30/60/90 paper based review.

An example of the use of the Kaizen Burst was in meeting the 3-week mill order date by eliminating wasteful activities inherent in 2D paper-based delivery at handoffs between A/E and the fabricator. The A/E and the fabricator agreed to utilize intelligent 3D model exchange. The A/E's 3D analysis model was transmitted directly to the steel fabricator, who imported it into the detailing software and extracted steel quantities directly from the 3D model (see Figure 4 -2). This allowed the key mill order date of 3 weeks to be met and the fabricator was able to start the detailing process early. The fabricator continued to submit weekly up-to-date steel 3D models to the A/E, which were distributed to the design/build team for coordination.

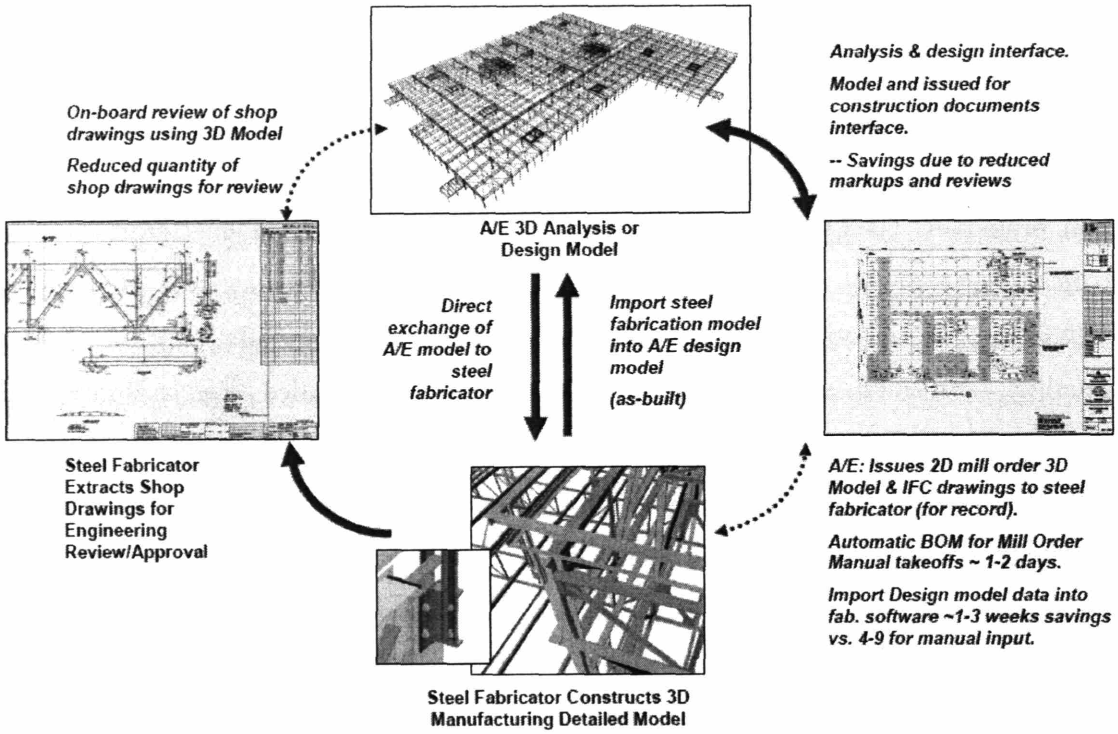

Figure 4-2 Eliminating Waste at Handoffs[20]

Not only did the use of 3D BIM allow thousands of interferences to be detected and resolved prior to construction, the final 3D models were fully detailed to the installation level, which allowed the sub-contractors to maximize the benefits of off-site fabrication and pre-assembly. They were able to produce detailed quantity takeoffs and order material exactly as required. By delivering Just In Time (JIT) to the construction site, the time spent at the construction site was significantly reduced. It also allowed components to be installed to very tight tolerances, reducing waste. The construction site was well organized—construction crews rarely overlapped and dumpsters remained empty during construction due to the increased use of offsite fabrication, pre-assembly, and JIT delivery. Structural steel erection was completed 35 days early, with no changes during installation. MEP systems were also installed without any field rework. Installation of piping and HVAC systems was completed during the first few months of construction. The elimination of field changes, as well as reduction in the movement of people and

[20] Courtesy of GHAFARI Associates, Flint project

material, improved site safety. The elimination of field changes also improved morale—workers took pride in their work by knowing they were installing it right the first time. The project was finally delivered to General Motors almost 5 weeks ahead of schedule (15% accelerated) with virtually no field overtime.[21]

[21] Courtesy of GHAFARI Associates, Flint Project

CHAPTER 5- Lean Construction Institute (LCI)

The Lean Construction Institute (LCI), is a non profit research organization, founded in August 1997 by Glenn Ballard and Gregory A. Howell . LCI's purpose is to reform the management of work in design, engineering and construction for capital facilities. LCI has developed the Lean Project Delivery System (LPDS), and the Last Planner System of production Control.

Section 5.1 – Lean Project Delivery System Developed by LCI

LCI's mission is to develop a new and better way to design and build capital facilities. They call this new way Lean Project Delivery System (LPDS). Their current LPDS model consists of 13 modules, 9 organized in 4 interconnecting triads or phases extending from project definition to design to supply and assembly, plus 2 production control modules and the work structuring module, both conceived to extend through all project phases, and the post-occupancy evaluation module, which links the end of one project to the beginning of the next (Figure 5-1). In the subsequent sections of this chapter an analysis of how the developed LPDS is designed to work will be discussed.

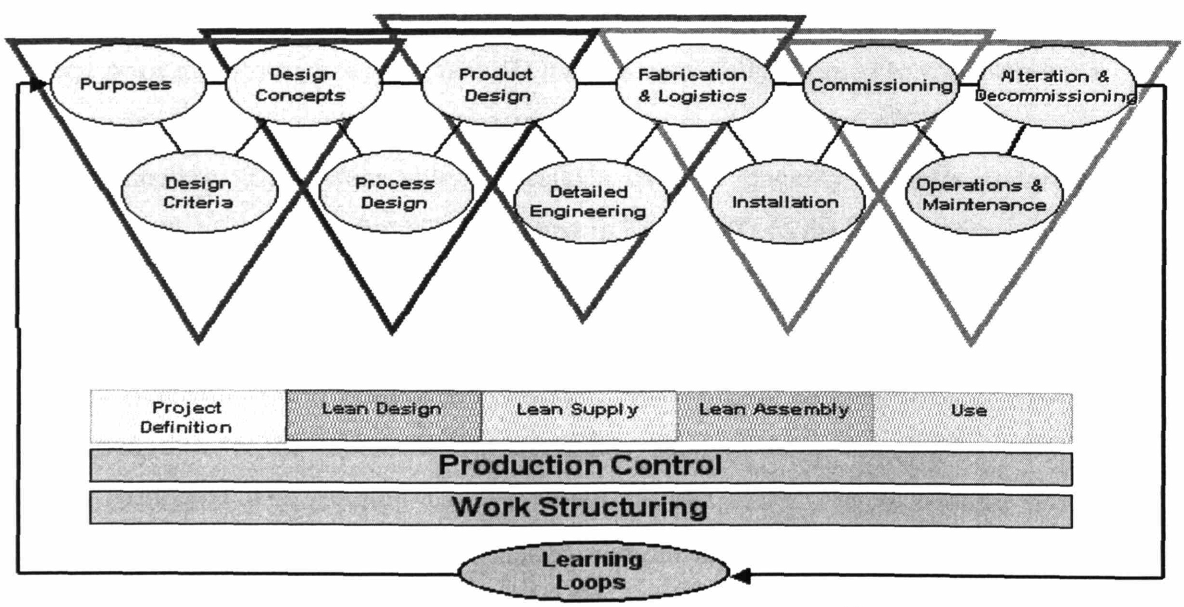

Figure 5 -1 Lean Project Delivery System[22]

[22] Lean Construction Institute

Section 5.1.1 – Project Definition

The project definition phase is designed to be managed by the project manager responsible to the client for the entire project, including both designing and building. The project manager may use traditional sources as inputs, such as architectural programming, but such inputs will be integrated with others, including post-occupancy evaluations.

Costing and project duration estimating is integrated with the production of the project definition, rather than being done after the definition is produced. When appropriate, target costs are established for the facility to be designed. Otherwise, the client will make a decision regarding cost within the definition process. Target costs are appropriate when the facility is analogous to a product to be sold. Such is the case for clients whose business case is based on a return-on-investment strategy; such as, commercial building developers. Target costs may be inappropriate for institutional facilities and other situations where the amount of funding is driven more by desired prestige or style, and where funding is often somewhat elastic. For example, MIT won't build a library unless they can get a facility that meets their desires for a certain impact or statement. If they need more money, they will go back to their alumni and other donors. Should they be unable to get the money, and if they aren't forced by capacity, structural, or code considerations to build a new library, they won't build one at all.

Design criteria for both product and process are produced. Multiple conceptual designs are generated and evaluated. When appropriate, more than one conceptual design is carried into the Lean Design phase.

Conceptual designs are generated and evaluated in dialectic with Needs Determination and Design Criteria development. The project definition process includes an explicit information collection and documentation process. Needs are translated into design criteria using techniques derivative from Quality Function Deployment.[23]

[23] Herman G. Ballard, The Last Planner System of Production Control, Doctoral Thesis, University of Birmingham, 2000.

Collaborative production and decision making includes clients and stakeholders; e.g., design and construction specialists; suppliers of materials, equipment, and services; facility operators, maintainers, and users; representatives of financiers, insurers, regulators, and inspectors.

Work structuring is applied in the project definition phase in the production of rough cut strategies and plans for project execution, linked to product architecture options, in advance of the more detailed integration of product and process design to be accomplished in subsequent phases.

Production control is applied in the project definition phase once a schedule for the phase has been developed. The first schedule is no more than fitting the steps of the project definition process within the available start and completion dates. Theoretically the Project Definition is to transition to Lean Design when there is alignment between:

- customer needs and stakeholder demands
- design criteria for product and process
- conceptual design(s)

Section 5.1.1 – Lean Design

The Lean Design phase develops the conceptual design from Project Definition into Product and Process Design, consistent with the design criteria produced in Project Definition.

Product and process design decisions are made with a view to customer needs as well as to design criteria. Should an opportunity emerge for increasing customer value by expanding customer needs, and if there is sufficient time and money, the project definition process is reengaged to align needs, criteria, and design concepts.

Product and process design decisions are made simultaneously rather than first producing a design for the product, then trying to produce a satisfactory design for the process of designing and making that product.

The first process designed is the design process itself. That is done by the design team using team planning techniques (stickies on the wall), employing the Activity Definition Model (ADM). The ADM is an input process-output representation of designs tasks, supplemented by specification of criteria and of resources and an inspection process resulting either in redo or release to the customer process. (Figure 5-2)

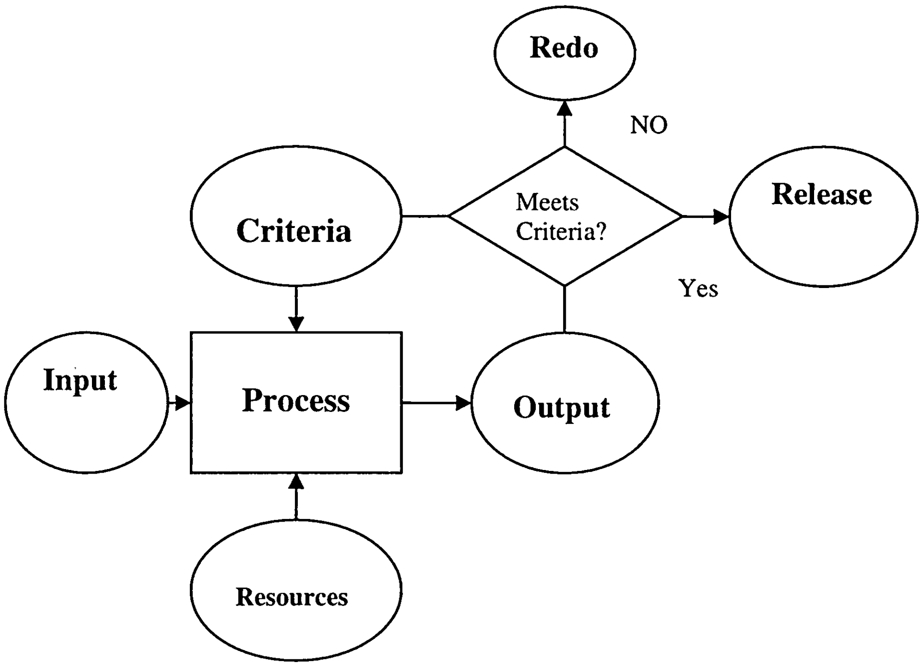

Figure 5-2 Activity Definition Model (ADM)

One set of criteria/objectives for work structuring (integrated product and process design) is simplifying site installation to final assembly and testing.

Set Based Design (aka Set Based Concurrent Engineering) as practiced in Toyota's product development are developed into principles for process design.

The Design Structure Matrix is used to re-sequence design tasks in order to reduce needless iteration. Every effort is made to maximize customer value in the making of trade-offs between needs and objectives.

A single conceptual design is normally selected before the end of this phase because the last responsible moment for making that decision will have usually passed. Design decisions are deferred until the last responsible moment if doing so offers an opportunity to increase customer value.

Production control is applied to the Lean Design phase using standard Last Planner procedures and techniques.

Specialty contractors serve as designers or participate in the design process, assisting with selection of equipment and components and with process design. Where specialty contractors do not perform the design, designers will produce only those deliverables needed for permitting and needed by specialty contractors or other suppliers for detailing. For example, the mechanical engineer will produce only single lines of HVAC duct.

The Lean Design phase transitions into Lean Supply when the product and process design have been developed from the design concept consistently with design criteria, which are themselves adequate expressions of customer needs and stakeholder demands. This alignment is explicitly examined and agreed by the design/build team and the client before transition.

"Work Structuring" is a term created by LCI to indicate the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts. The purpose of work structuring is to make work flow more reliable and quick while delivering value to the customer.

Work structuring is used as the fundamental level of process design, answering questions such as[24]: In what chunks will work be assigned to specialist production units (PUs)? How will work chunks be sequenced through various PUs? In what chunks will work be released from one PU to the next? Where will decoupling buffers be needed and how should they be sized? When will the different chunks of work be done?

Work structuring decisions are made in all project phases. For example, decisions regarding supply chain structure may be made in the project definition phase, while

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[24] Herman G. Ballard, The Last Planner System of Production Control, Doctoral Thesis, University of Birmingham, 2000.

seemingly small details like the selection of a specific component in detailed engineering can impact how work flows within the assembly process.

Section 5.1.1 – Lean Supply

The Lean Supply phase consists of detailed engineering of the product design produced in Lean Design, then fabrication or purchasing of components and materials, and the logistics management of deliveries and inventories.

All decisions regarding the engineering, production, or delivery of materials and components are made with an eye to maximizing customer value. 3D modeling is used for detailed engineering. Where possible, fabrication is driven directly from the 3D model. Collaborative design tools are used to integrate design inputs developed on different platforms into a single model.

Process design addresses buffer type, location, and sizing. That is further detailed and then controlled in this phase, in which the 'iterative' relationship among the modules within the phase are more like continuous adjustment than like the generative conversation characteristic of design proper.

This phase is designed to apply lean manufacturing techniques to fabrication shops. In this phase of the project, which is a temporary production system, is physically linked to the supply chains that exist independently of the project. This is designed to reduce costs and lead times.

An objective of process design is to minimize inventories, right sizing them to the flow variability that cannot be eliminated. This phase transitions into Lean Assembly once site deliveries begin. Site deliveries may be initiated within a fast tracking strategy that decouples facility systems or components so that assembly of one component can begin while detailed engineering of subsequent components is still underway.

Section 5.1.1 – Lean Assembly

Lean Assembly begins with the first delivery of tools, labor, materials or components to the site and ends when the keys are turned over to the client. A key issue is coordination of deliveries to ensure soundness of assignments while sizing buffers to residual variability. An objective is to approximate one-touch material handling ideals. Since considerable waste and value loss is found in inspection.

In addition, the assembly process promotes multiskilling in shops and site installation. Multiskilling is best initiated within the context of continuous flow processes, as a means for fine balancing. From there, it can be extended to the objective of minimizing total site head count.

Section 5.1.1 – Production Control

"**Last Planner**" is the name for the LCI's system of production control. Production control governs execution of plans and extends throughout a project. "Control" in this context is to mean causing a desired future rather than identifying variances between plan and actual.

Production control consists of work flow control and production unit control. Work flow control is accomplished primarily through the look ahead process. Production unit control is accomplished primarily through weekly work planning.

Front end planning belongs to the project definition and design phases of projects. One of the products of front end planning is master schedules. Master schedules serve specific purposes; e.g., demonstrating the feasibility of project completion by target end date. Those purposes or functions do not require a high level of detail, which most often is inappropriate because of uncertainty regarding the future.

Master schedules are expressed at the level of milestones, typically by phase. Phase schedules are produced by cross functional teams using pull techniques near in time to the scheduled start of the phase. Phase schedules feed into look ahead windows, usually 3 to 12 weeks in duration. Lookahead processes make scheduled tasks ready for assignment. Such tasks are placed in Workable Backlog.

Tasks are allowed to maintain their scheduled starts only if the planner is confident they can be made ready in time. Scheduled tasks are made ready by screening for constraints, then by assigning make-ready actions to remove those constraints. The lookahead process generates early warning of problems so there is more time to resolve them.

Weekly work plans are formed by selection of tasks from Workable Backlog. Every effort is made to to make only quality assignments; i.e., those that are well defined, sound, in the proper sequence, and sized to capacity. The percentage of planned assignments completed (PPC) is tracked and reasons for non-completions are identified and analyzed to root causes. Action is taken on root causes to prevent repetition.

Section 5.1.2.1 - Last Planner System

In a dynamic environment like the AEC industry deciding what and how much work is to be done next by a design team or construction crew is rarely a matter of simply following a master schedule established at the beginning of the project. How are such decisions made and can they be made better? These questions were the drivers of initial research in the area of production until level planning and control under the title of the "Last Planner" by Ballard and Howell in 1997.[25]

Section 5.1.2.2 – Should-Can- Will

Last Planner can be understood as a mechanism for transforming what should be done into what Can be done, thus forming an inventory of ready work, from which Weekly Work Plans can be formed. Including assignments on Weekly Work Plan is a commitment by the Last Planners to what they actually WILL do.

Ballard explains that last planner performance is evaluated as if there could be no possible difference between SHOULD and CAN. "What will we do next week?" "Whatever is on the schedule", or "Whatever is generating the most heat." Supervisors

[25] Ballard, Herman, G., The Last Planner System of Production Control, Doctoral Thesis at the University of Birmingham.

consider it their job to keep on subordinates to produce despite obstacles. Failure to proactively control at the product unit level increases uncertainty and deprives workers of planning as a tool for shaping the future. Figure 5-3 represents the formation of assignments in the Last Planner planning process.

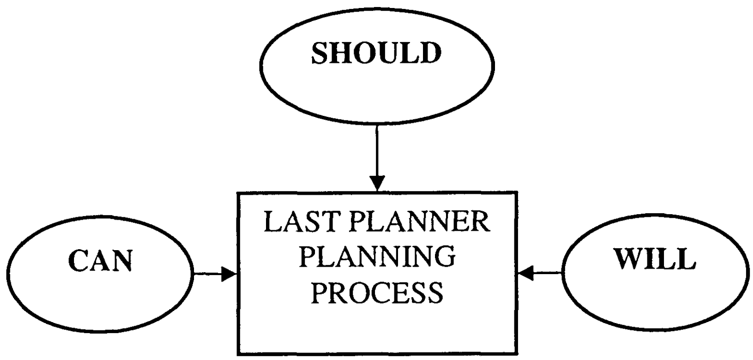

Figure 5-3 The formulation of assignments in the Last Planner planning process[26]

Section 5.1.2.3 – Production Unit Control

The Last Planner process requires four quality characteristics in developing assignments, which are:

The assignment is well defined

The right sequence of work is selected

The right amount of work is selected

The work selected is practical or sound (can be done)

By "well defined" Ballard means sufficiently that it can be made ready and completion can be unambiguously determined. The "right sequence" is the sequence consistent with the internal logic of the work itself, project commitments and goals, and execution strategies. The "right amount" is that amount the planners judge their production units

[26] Last Planner

capable of completing after review of budget unit rates and after examining the specific work to be done. "Practical" means that all prerequisite work is in place and all resources are available.

The unit of measure used to see if what was committed to do (WILL) was realized is Percent Plan Complete (PPC). PPC is the number of planned activities completed divided by the total number of planned activities, expressed as a percentage. For example given quality plans, a higher PPC corresponds to doing more of the right work with given resources.

Section 5.1.3 – Work Flow Control

The basis of work flow control for the LPS is to cause work to move between production units in a desired sequence and rate. Production Unit Control coordinates the execution of work within production units such as construction crews and design teams.

Work Flow Control coordinates the flow of design, supply, and installation through production units. In the hierarchy of plans and schedules, the lookahead process has the job of work flow control. Lookahead schedules are common in current industry practice, but typically perform only the function of highlighting what SHOULD be done in the near term. In contrast, the lookahead process within the Last Planner system serves multiple functions. It shapes the workflow sequence and rate, matches work flow and capacity, decomposes master schedule activities into work packages and operations, develops detailed methods for executing work, maintains a backlog of ready work and updates and revises higher level schedules as needed. These functions are accomplished through various specific processes, including activity definition, constraints analysis, pulling work from upstream production units, and matching load and capacity.

The vehicle for the lookahead process is a schedule of potential assignments for the next 3 to 12 weeks. The number of weeks over which a lookahead process extends is decided based on project characteristics, the reliability of the planning system, and the lead times for acquiring information, materials, labor, and equipment. Prior to entry into the lookahead window, master schedule or phase schedule activities are exploded into a level of detail appropriate for assignment on weekly work plans, which typically yields multiple assignments for each activity. Then each assignment is subjected to constraints analysis to determine what must be done in order to make it ready to be executed. The general rule is to allow into the lookahead window, or allow to advance from one week to the next within the lookahead window, only activities that can be made ready for completion on schedule. If the planner is not confident that the constraints can be removed, the potential assignments are retarded to a later date. Figure 5-4 is a schematic of the lookahead process, showing work flowing through time from right to left. Potential assignments enter the lookahead window 6 weeks ahead of scheduled execution, then move forward a week each week until they are allowed to enter into workable backlog, indicating that all constraints have been removed and that they are in the proper sequence for execution. If the planner were to discover a constraint perhaps a design change or acquisition of a soils report) that could not be removed in time, the assignment would not be allowed to move forward. The objective is to maintain a backlog of sound work, ready to be performed, with assurance that everything in workable backlog is indeed workable. Weekly work plans are then formed from workable backlog, thus improving the productivity of those who receive the assignments and increasing the reliability of work flow to the next production unit.

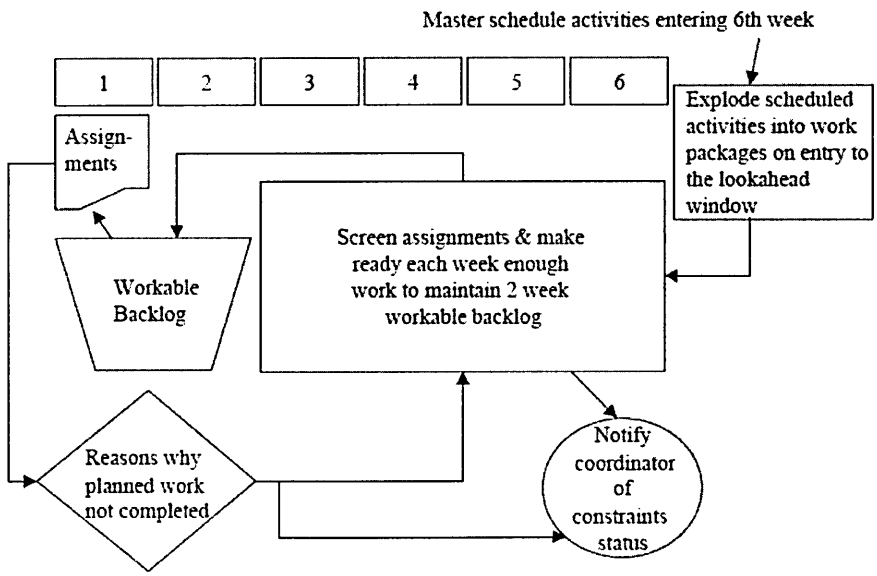

Figure 5-4 The Look Ahead Process[27]

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[27] Last Planner

Section 5.1.4 – Constraints Analysis

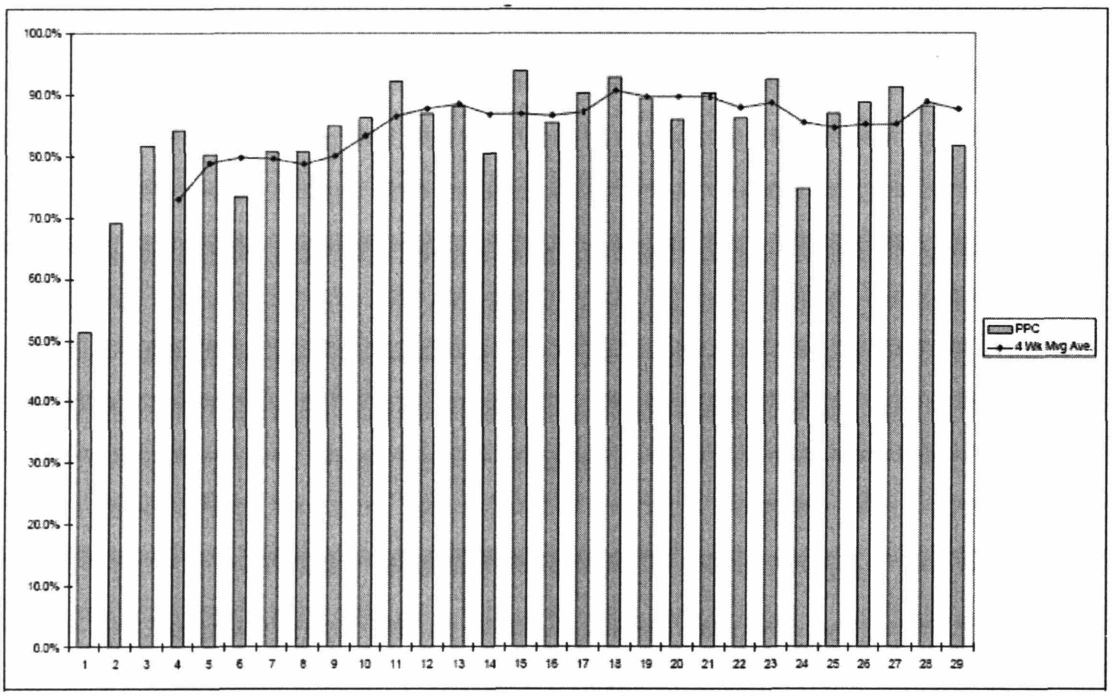
Once assignments are identified, they are subjected to constraints analysis. Different types of assignments have different constraints. Some common constraints are design, submittals, materials, prerequisite work, space, equipment, and labor. The constraint analysis allows for an inspection of any long lead items or coordination that may cause delays. Design constraints can virtually be the clarity of directives such as: level of accuracy required, prerequisite work (data, evaluations, models), labor and technical resources. A great benefit to constraints analysis is that it requires suppliers of goods and services to actively manage their production and delivery, and provides the coordinator with early warning of problems, hopefully with sufficient lead time to plan around them. In the absence of constraints analysis, the tendency is to assume a throw-it-over-the-wall mentality; to become reactive to what happens to show up in your in-box or laydown yard.

Section 5.1.5 – Application of the Last Planner System

Linbeck Construction, a founding member of the Lean Construction Institute, was the GC for Rice University's Old Chemistry Building Renovation Project in Houston, Texas. Kathy Jones, Linbeck's project manager, decided that she would use the LPS to manage this project. In preparation Jones' project personnel, including the architect, conduct several educational and training sessions on the LPS. Unfortunately, the architect refused to participate in the Last Planner System. However, the subcontractors became totally committed and enthusiastic about the planning process during the course of the job, as did Rice University's personnel. The project was completed to a very aggressive schedule to the satisfaction of users and within the budget. Rice University was so well pleased with the performance that Linbeck won it's Fondren Library Project, and is well situated to do roughly half a billion dollars worth of work in the Rice University.

<u>Success</u>

While using the LPS PPC rose to a level of 85 % over a period of approximately eleven weeks, then stabilized at that level for the duration of the project. This was an unprecedented accomplishment at the time, and resulted from the dedication of the owner, general contractor, and subcontractor personnel to the Last Planner System and its goal of plan reliability. Kathy Jones reinforced the Last Planner principles by fining those who used the expression 'I hope' or 'hopefully' in connection with a commitment to do work. See Figure 5-5.



Date	1/25/99	2/1/99	2/8/99	2/15/99	2/22/99	2/29/99	3/8/99	3/15/99	3/22/99	3/29/99	4/5/99	4/12/99	4/19/99	4/26/99
Tasks Completed	20	38	40	48	49	44	46	46	56	57	71	66	66	66
Tasks Assigned	39	55	49	57	61	60	57	57	66	66	77	76	75	82

Date	5/3/99	5/10/99	5/17/99	5/24/99	6/1/99	6/7/99	6/14/99	6/21/99	6/28/99	7/6/99	7/12/99	7/19/99	7/26/99
Tasks Completed	60	53	65	64	50	55	65	69	62	62	66	63	73
Tasks Assigned	64	62	72	69	56	64	72	80	67	83	76	71	80

Date	8/2/99	8/9/99
Tasks Completed	59	53
Tasks Assigned	67	65

Figure 5-5 Old Chemistry Building PPC Graph and Data

Failures

Of the relatively few failures to complete weekly assignments, most were caused by lack of manpower or failure to complete prerequisite work ("make ready"). The remaining cause categories were Schedule Accuracy (the assignment shouldn't have been made), Material Deliveries, Design Coordination, Equipment (part of the building, not construction equipment), Rework, Weather, and Overcrowding. See Figure 5-6.

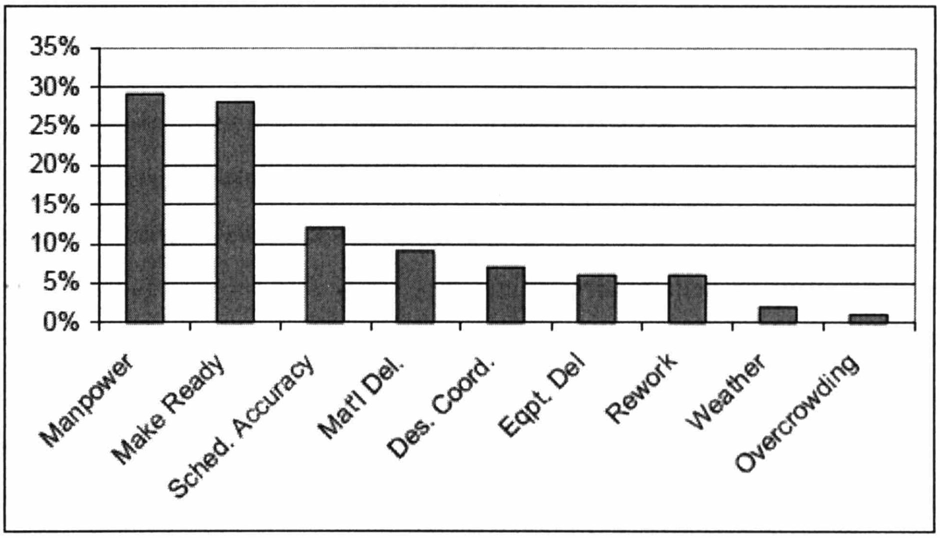


Figure 5-6 Reasons for Non-completions

Lack of participation by the architect was a serious deficiency on the project, perhaps concealed by the high PPC and low incidence of design coordination as a reason for failing to complete weekly work plan assignments. Design problems did impact the job, but that impact would only be evident in schedule changes and in the lookahead process.

Overall the use of LPS was a success and Jones contributes this the collaboration between the customer and the subcontractors.

Section 5.3 – Case Studies of "Lean Construction"

The benefits of Lean Construction are slowly spreading amongst the construction industry. Although Lean Construction is still in its infancy stages, construction firms are realizing that cost and time benefits on large complex building systems from applying

Lean Construction theories are providing a competitive edge. In this section a medical facility project will be presented where the GC utilized Lean Construction theories to manage the design and construction of the project.

Section 5.3.1– Camino Project

Early involvement of key subcontractors in a design-assist process on the Camino project is an example of getting the process knowledge to design a better and more constructible product. Merging product and process also helped maximize the available information on the front end.

For the Camino project, 3-D and 4-D modeling, which takes into account the three spatial dimensions, length, width and height, and adds the temporal, time, was used during design coordination to help communicate sequencing, allowing the project team to best understand and take advantage of potential time and space conflicts.

Camino Parking Structure & Medical Building is a 250,000 SF medical and office building and 400,000 SF parking structure construction design project, awarded to DPR Construction for 148 Million Dollars. Initially the Camino Team started with traditional division into Architect-Owner Build Team, organized into silos by discipline and organization barriers to direct and open communication much like Figure5-7. Their first challenge was to convert their organization and subcontract partnerships into an integrated, collaborative team with direct communication (Figure 5-8),that would support their Lean Project Delivery.

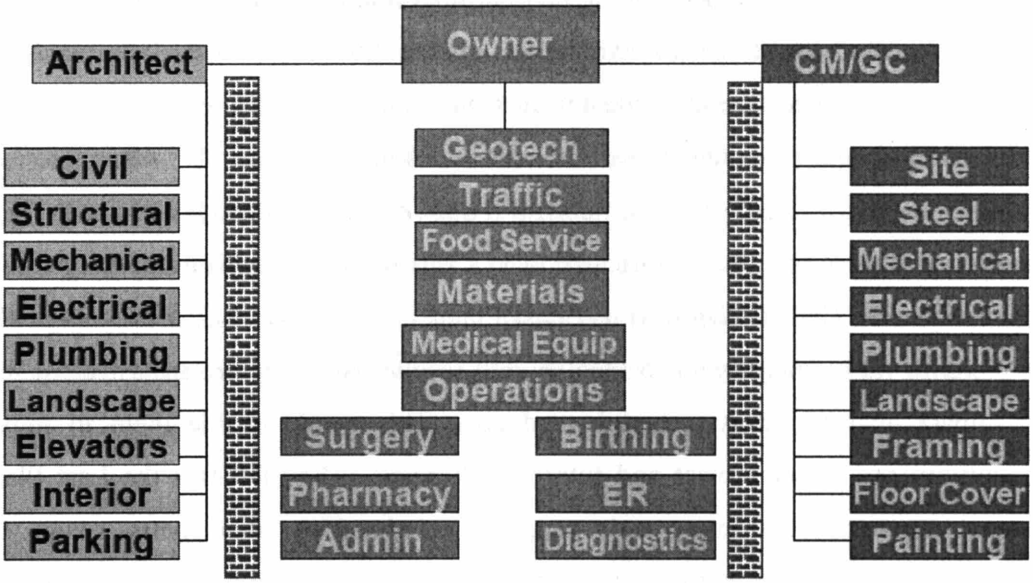


Figure 5-7 Traditional Architect-Owner Builder Organization[28]

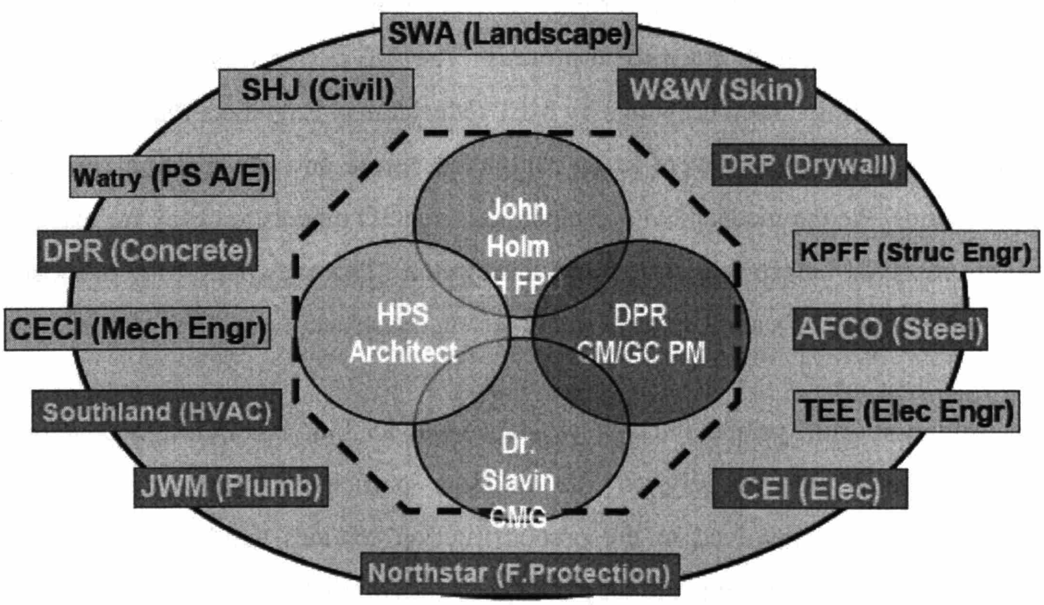


Figure 5-8 Integrated Organization with Leadership Involved[29]

DPR's Lean Project Delivery was centralized around three main theories. They were Target Costing, Applying the Last Planner System and Building in 3D before

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[28] Pixlery, David,Applying Lean Principles to Healthcare Construction, LCI Symposium 2006
[29] Pixlery, David,Applying Lean Principles to Healthcare Construction, LCI Symposium 2006

constructing. The first was set around their cardinal rule that "Target Cost Can Never Be Exceeded". This was done to avoid last minute budget busts and surprises. The contractors need to reduce lag time for cost and constructability feedback. This meant that the A/E's couldn't set design without cost reviews.

The second part of the Camino Lean Project Delivery was based on applying the Last Planner System. Their decision to use Last Planner System was based on being able to use planning and management to identify and resolve issues before they became crises and impact quality, safety, schedule and cost. This would enable them to improve productivity and lower project and future work costs. They felt that the Last Planner System promotes customer and supplier relationships that help setup High Visibility/Accountability performance at all levels starting with the owner-architect-contractor.

The third part of the Camino Lean Project Delivery was to incorporate 3D modeling into their design and construction approval process. The A/E design was to be translated into 3D Object Modeling. Shop drawings by MEP (Mechanical Engineers Plumbers) and Fire Protection (FP) contractors were to be completed before any construction commenced. Other systems like the mechanical and electrical used 3D models to check for clashes and conflicts resolved before fabrication and installation This was done to avoid lost time and expense from RFI's and Change Orders during construction.

At the midpoint of the project the cost avoidance was $5,356,980 of Design Development. DPR contributes this entirely to the builders participated early in design, key subcontractors were involved in the preconstruction services that enabled a continual flow. DPR's project manager said they brought builders, such as GC/concrete & drywall, design assists/build HVAC, plumbing, electrical & fire protection and steel and skin, on board very early in design. The purpose of this is was solely to improve constructability and control cost.

The project is still under construction but is already being used as a model to follow for good Lean construction practices. DPR does admit that although bringing in the subcontractors early in the design phase was extremely beneficial they did encounter some challenges. It was difficult for the A/E to accept the builder's involvement in design. The general contractor also found it difficult allowing the subcontractors provide a greater role. Also, the 3D system was a true asset buy money and time had to worked into the budget and schedule to ensure the project kept flowing. In addition, managing the handoff between the A/E and the modeling engineers had to be carefully monitored.

Part II – ANALYSIS OF CURRENT DESIGN PROCESS

CHAPTER 6: Construction as Flow in Design

Section 6.1- Flow process in construction

In Part I inherit problems of traditional construction practices were presented; in this part an analysis of the cause of these problems will be discussed.

Section 6.1.1 – Overcoming Flow Problems in Construction Design

As presented in Part I the construction design process can be a key driver in preventing flow. Errors and bad decisions made early in the design can be costly and have impacts on the entire lifecycle of a project.

The cost of design is made up of costs of value-adding activities and waste. The waste is in the design process is formed by two major components:

1) Rework (due to design errors detected during design)
2) Non value adding activities in information and work flows.

The design process has two customers: the construction process and the client. The value the client is determined by three variables.

1.) How well the implicit requirements have been converted into a design solution.
2.) The level of optimization achieved.
3.) The impact of design errors that are discovered during start-up and use.

The inherent waste in construction process is created by:

1) Rework due to design
2) Non-value adding activities and work flow, such as waiting, moving, inspecting, duplicated activities and accidents.

The primary focus in design is thus minimizing value loss, where as in construction it is on minimizing waste. It has to be stressed that both wastes and value losses are real and considerable.

Due to the one-of a kind character of construction, it is necessary to have two time frames for analysis: a project time frame and a longer time frame. From the viewpoint of particular one-of-a-kind project, the goal is to attain the level of cost and value of the best existing practice as presented in Figure 6-1.

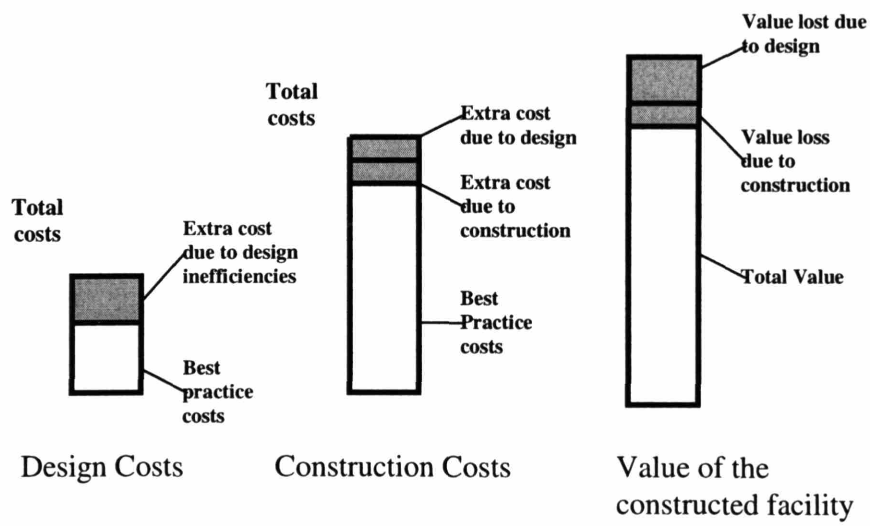

Figure 6-1 Decision Situation from client's point of view

From the longer term point of view, the organizations in construction have to improve processes continuously in order to meet and beat the best practice. However, even the best practice has an ample reserve of improvement potential and the efficiency of the best or at least should be continuously moving as presented in Figure 6-2.

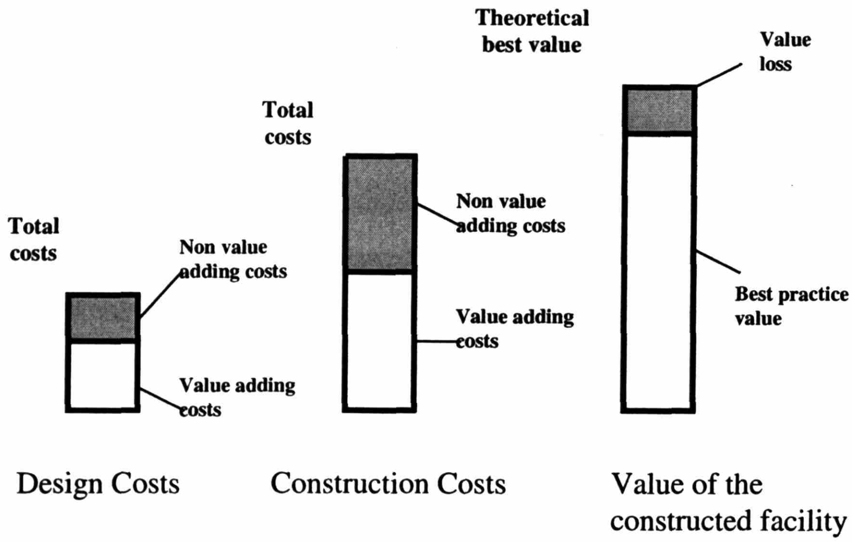

Figure 6-2 Decision Situation from an organizations point of view

By setting a framework of time there is process improvement. Although the above may appear that there is a loss of potential innovation to improve conversion process, innovation is closely related to process improvement.[30]

The time and value are influence by decisions in the project, which are used to manipulate flow characteristics. Therefore the cost, time and value are dependent on the long term efforts of participating organizations for continuous improvement.

Section 6.1.2 – Improving Quality

In order to improve quality the basic lean principles of reduced variability should be incorporated. The design should allow for improved processes to have low variability and allow for a flow of design that enables a means for rapid detection and correction. The flow of design and improvement principles concerning variability, cycle time are inherit to meeting customer requirements and providing value.

[30] Ballard, Glenn (1996b). "Can Pull Techniques Be Used IN Design?" Proceedings of the Conference on Concurrent Engineering in construction, Espoo, Finland, August 1999.

Section 6.1.3 – Non-segmented control

The basic solution is, of course, to focus control on complete flow process. As presented in Part I the segmented control is detrimental to a systematic process solution. To focus on a complete control, this means that flow is the basis for organization, rather than specialties or functions as in the hierarchical organization. For example, a component manufacturer should be responsible for the whole material chain, including the installation on site. In design, this would mean that the subcontractor that provides information during the design should be the subcontractor that is contracted to perform the installation.

Section 6.1.4 – Eliminating Negative Iteration/Design Sharing

Deferred commitment is a strategy for avoiding premature decisions and for generating greater value in designs. It can reduce negative iterations by simply not initiating the iterative loop. Also aligning the solution space and setting design boundaries so all designers are aware of the design space which has been finalized and not likely to change. IT technology enables the sharing of updated designs. Software programs such as WebCM allow for A&E firms to share their designs on a more iterative base, with the benefit of not having to be physically present. Another related but extreme solution to reduce negative iteration is that of "least commitment". Least commitment is to systematically defer decisions until the last responsible moment.

CHAPTER 7: System Dynamics Model of Design Errors

Section 7.1 – System Dynamics Introduction

Jay Forrester pioneered the field of system dynamics, the analysis of behavior of systems, in 1961. The methods of systems dynamics provide us with tools for better understanding difficult management problems. The methods have been used for over thirty years and are now well established. However, these approaches require a shift in the way we think about the performance of an organization. In particular, they require that we move away from looking at isolated events and their causes, and start to look at the organization as a system made up of interacting parts.[31] The use of system dynamics although initially intended as "a practical tool that policy makers can use to help them solve the pressing problems they confront in their organizations"[32] has proven useful in modeling decision making and organizational behavior. The availability of visual modeling and simulation software has also contributed significantly in making the methodology popular. Today there are at least three visual modeling and simulation softwares (STELLA, VENSIM and POWERSIM) available commercially to develop and test systems dynamics models; this study will utilize VENSIM. The elements of system dynamics diagrams and modeling are feedback, accumulation of flows into stock and time delays.

Section 7.1.1 – Causal Loops and System Behavior

This linkage between structure and behavior remains the guiding principle for practitioners of systems dynamics. Therefore the basic structural element of system dynamics is the feedback loop; the underlying structure refers to the collection of interacting feedback loops comprising the system. Modeling in system dynamics starts with identification of the reference mode behavior time dependent behavior of one or two important variables of the system, the dynamics of which the model would try to explain. The next step involves creating a causal loop diagram, a pictorial representation of the underlying structure that is thought to explain the reference mode behavior. Typically, modelers and subject matter experts will be involved in the process of arriving at a causal

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[31] Craig W. Kirkwood, System Dynamics: A Quick Introduction,1998
[32] Sterman, p. ix.

loop diagram. The causal loop diagram aids in visualizing how interrelated variables affect one another. The diagram consists of a set of nodes representing the variables connected together. The relationships between these variables, represented by arrows, can be labeled as positive or negative.

Depending on the polarities of causal links present, a feedback loop can generate one of two types of effects: a snowball effect, one in which a change in state generates action that causes a bigger change in the state, or a balancing effect where a change in state generates action to absorb the change. In the phraseology of system dynamics, these two loops are termed as reinforcing or balancing loops, respectively. A reinforcing loop generates exponential growth behavior (Figure 7-1). A balancing loop stabilizes the system around a target state (Figure 7-2). In a typical system, the presence of a number of such feedback loops of either type generates the complex dynamics of the system (Figure 7-3).

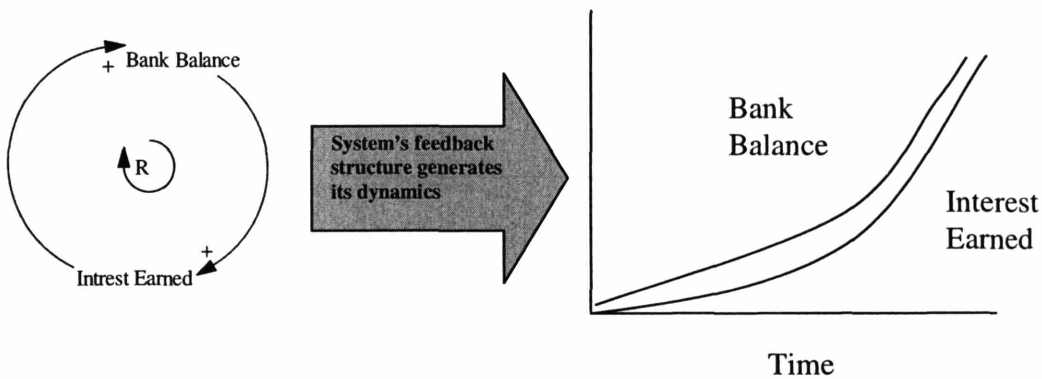


Figure 7-1 Reinforcing Loop

The amount of the Bank Balance will affect the amount of the Earned Interest as represented by an arrow pointing from Bank Balance to Earned Interest. Since an increase in Bank Balance result in an increase in Earned Interest, this link is positive. The Earned Interest gets added to the Bank Balance, also a positive link. The causal affect between these nodes forms a positive reinforcing loop, which is denoted with an "R".

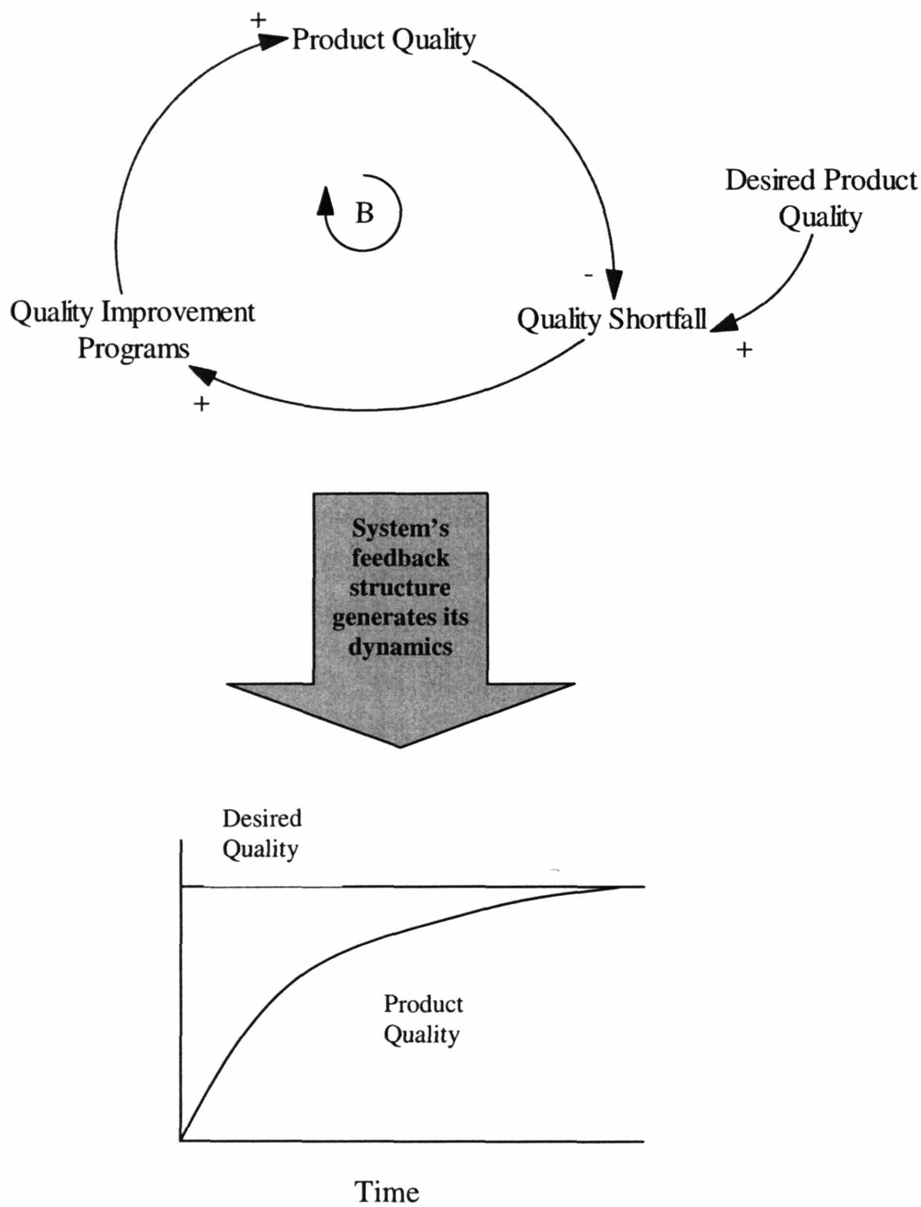


Figure 7-2 Balancing Loop

Balancing feedback operates whenever there is a goal-oriented behavior. If the goal is to have a Desired Product Quality then the system will compensate for the Quality Shortfall. The lower the quality the more Quality Improvement Programs will be started and presumably the deficiencies in quality will be corrected (reducing the quality shortfall).

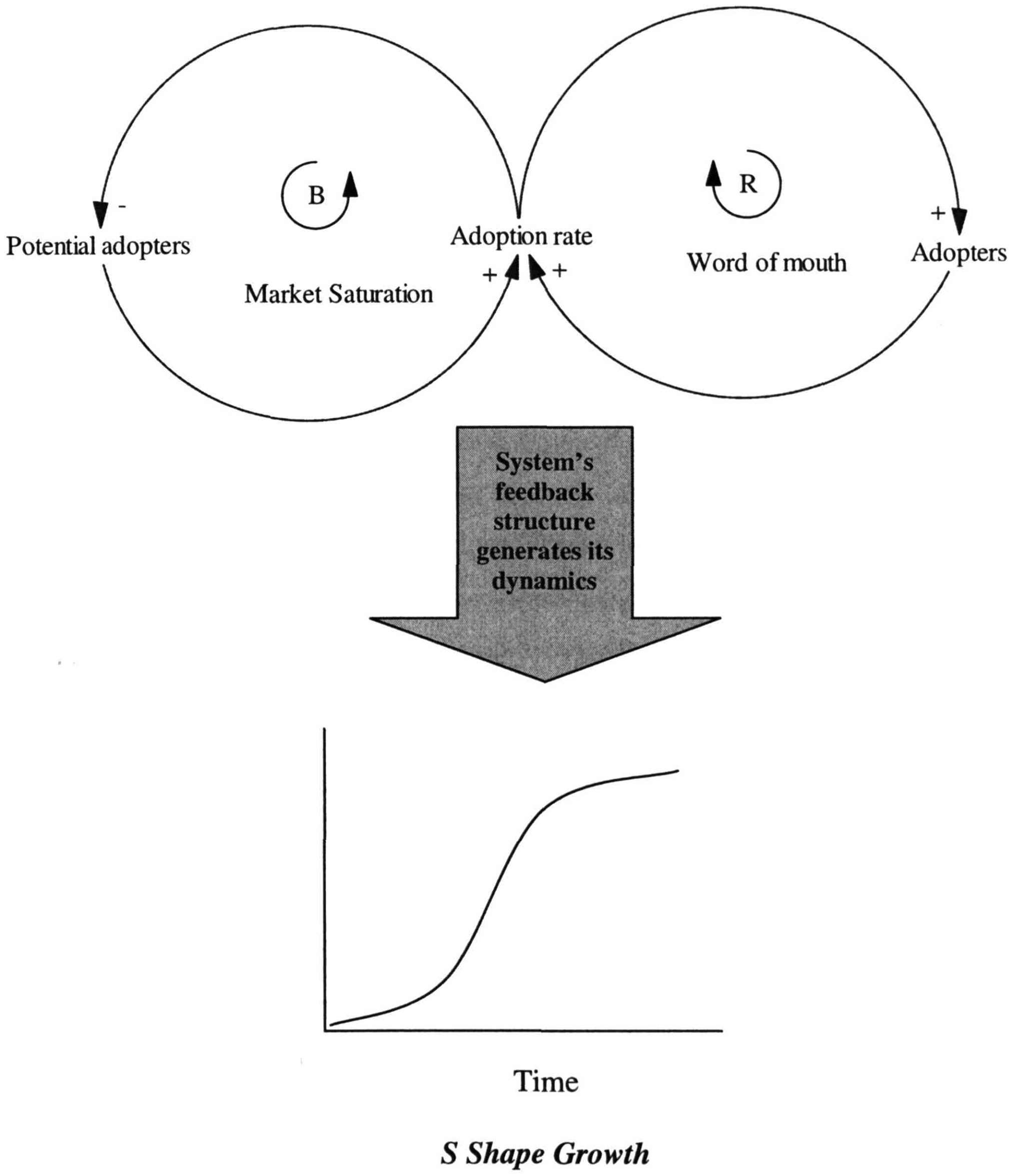


Figure 7-3 Interaction of Multiple Loops

There are two feedback loops in the diagram. The positive reinforcement loop on the right indicates that the more people have already adopted the new product, the stronger the word-of-mouth impact. There will be more references to the product, more demonstrations, and more reviews. This positive feedback should generate sales and continue to grow. The second feedback loop on the left is negative reinforcement. Clearly growth can not continue forever, because as more and more people adopt, there remain fewer and fewer potential adopters. Both feedback loops act simultaneously, but at different times they may have different strengths. Thus one would expect growing sales in the initial years and then the declining sales in the later years, as represented by the S growth curve.

Section 7.1.2 – Stock and Flows

As explained earlier, structure is made up of stocks and flows that make up important business processes and how these flows are controlled. A stock is the term for any entity that accumulates or depletes over time. A flow is the rate of change in the stock. For example, in a manufacturing firm, business processes center around flow of orders, flow of material, flow of skilled labor, flow of machinery and flow of money. Stock of materials determines the level of inventory held by a firm, the level of inventory decreases with the rate of Shipments and increases by the rate of Productions. Below is a simple Stock and Flow model.[33] (Figure 7-4).

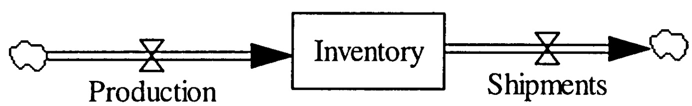


Figure 7-4 Stock and Flow

Section 7.2 – System Dynamics Model of Design Errors

Systems dynamics modeling is useful for managing complex processes that involve changes over time and is dependent on the feedback, transmission and receipt of information. The design process in a construction environment is extremely dynamic and complex. Invariability it consist of multiple interdependent components which have multiple interacting feedback process and non linear relationships.

It must be acknowledged that construction projects are also essentially human enterprises, and cannot be understood solely in terms of technical relations among components. Most of the date required to understand the evolution and dynamics needed to determine the

[33] Sterman, 191-194. Read Sterman's ***Business Dynamics***, Chapter 6, for more background information on Stocks and Flows.

variables that cause rework are concerned primarily with managerial decision-making and other so called "soft" variables, which contribute to the complex nature of the problem at hand.[34]

Section 7.2.1 – Description of Model

Typically rework originates in the design stage of a project. [35] Therefore the system dynamics model focuses on modeling and analyzing those factors that influence its occurrence during the design process. The model developed consists of the following interrelated sub-systems: 1. Process of designing tasks; 2. Error fraction in design (Adjusted Error Fraction); 3.Financial impacts of design errors; and 4. Project Completion timeline impacts of design errors. Below is the main system dynamics model that represents the flow of tasks in construction design. A larger view of the model can be found in Appendix B.

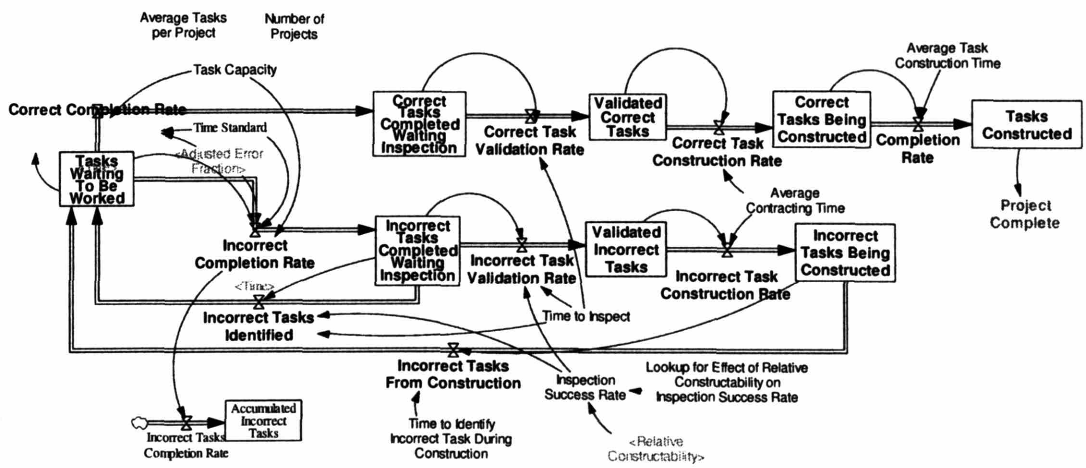


Figure 7-5 System Dynamics Model- Task Flow in Construction Design

Process of designing tasks

The process of completing tasks suggests that there are two possible design outcomes; the design is completed correctly or the design is done incorrectly. The model explores the dynamics that make up the error fraction, which drive the design to be completed incorrectly.

[34] Sterman,J.D. (1992) Systems Dynamic Modeling for Project Management, Working Paper, Systems Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA

[35] Burati et al., 1992 Causes of quality deviation in design and construction, ASCE Journal of Construction Engineering and Management, 118 (1), 34-49

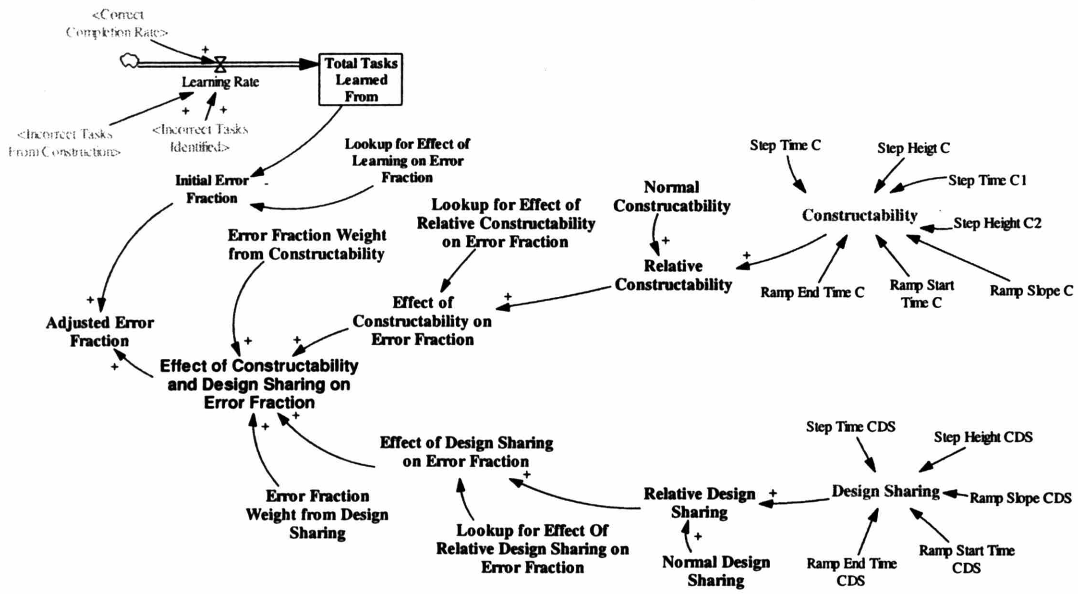


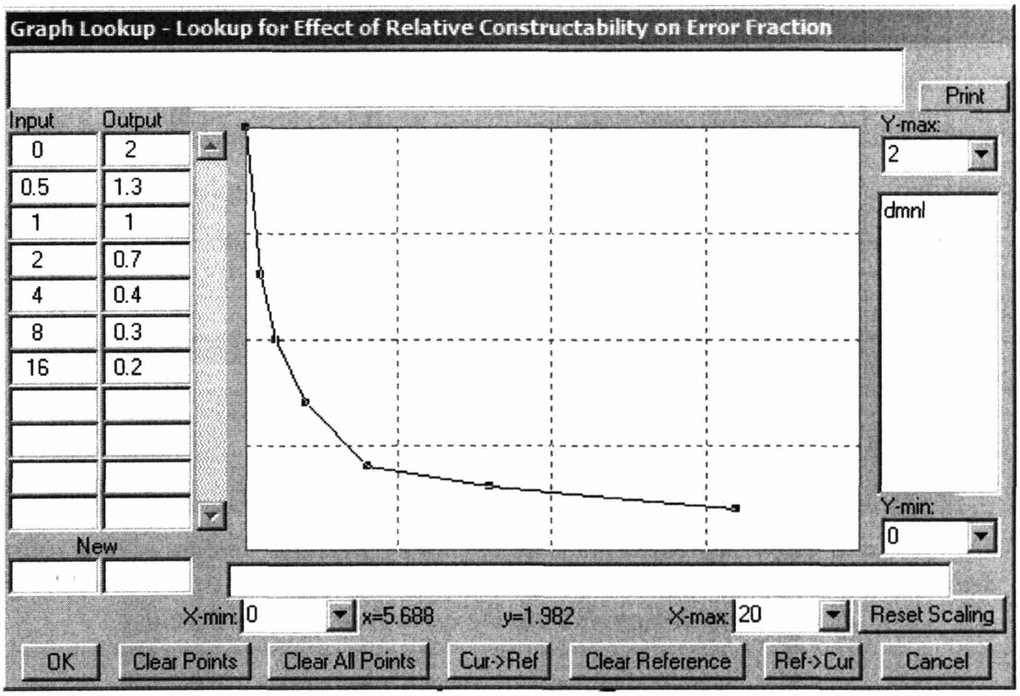
Figure 7-6 System Dynamics Model- Adjusted Error Fraction

<u>Error fraction in design</u>

The Adjusted Error Fraction in the model is determined by the product of the Effect of Constructability and Design Sharing on Error Fraction and Initial Error Fraction. The Effect of Constructability and Design Sharing on Error Fraction is determined by the effect each exogenous variable has on error fraction and it's corresponding Error Fraction Weight (Constructability - .78 and Design Sharing - .22) .

Constructability and Design Sharing are two exogenous variables that make up the Effect of Constructability and Design Sharing on Error Fraction. The Effect of Constructability on Error Fraction is determined by the Relative Constructability and the Lookup for Effect of Relative Construability on Error Fraction. Relative Constructability is composed of the Normal Constructability (.25) and the variable Constructability, which can be manipulated on a time scale. Vensim Analysis tools allows for the use of lookup tables to represent non linear outputs. Below is the table and graph representation which the model uses to determine the output value for the Lookup for Effect of

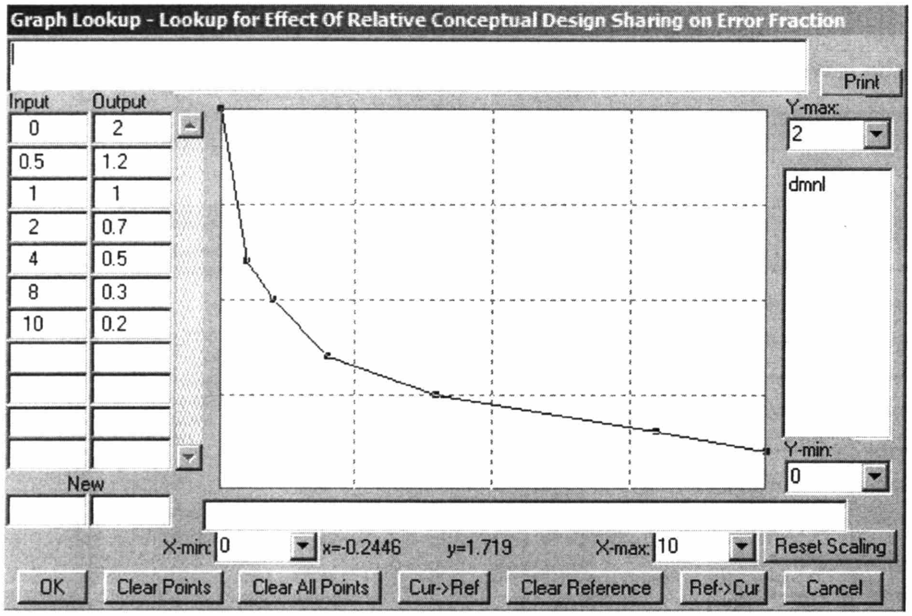
Constructability on Error Fraction. The more time spent conducting constructability reviews the lower the effect of relative constructability on error fraction.



The table and graph represent the relationship between the amount of time a firm dedicates to constructability and the effect on error fraction. As the more time is dedicated to constructability the error fraction is reduced.

Figure 7-7 Graph Lookup- Look up for Effect of Relative Constructability on Error Fraction

As mentioned above Design Sharing is the other exogenous variable that makes up the Effect of Constructability and Design Sharing on Error Fraction. Like Constructability the Effect of Design Sharing on Error Fraction is determined by a relative value and a graph lookup. Relative Sharing is composed of the Normal Design Sharing (.10) and the variable Design Sharing, which can be also be manipulated on a time scale. Current design teams meet traditionally 3 times after the conceptual design to share design changes. These meeting occur around the 30%, 60% and 90% design stages. The graph lookup that represents the relationship between the amount of design sharing and error fraction can be seen below (Figure 7-8).



The table and graph represent the relationship between the amount of time a firm dedicates to design sharing and the effect on error fraction. As the more time is dedicated to design sharing the error fraction is reduced.

Figure 7-8 Graph Lookup- Look up for Effect of Relative Design Sharing on Error Fraction

Initial Error Fraction

The Initial Error Fraction is the other variable that impacts Adjusted Error Fraction. Below is the portion of the system dynamics model that represents the impact that the Learning Rate and Total Tasks Learned From affect the Initial Error Fraction.

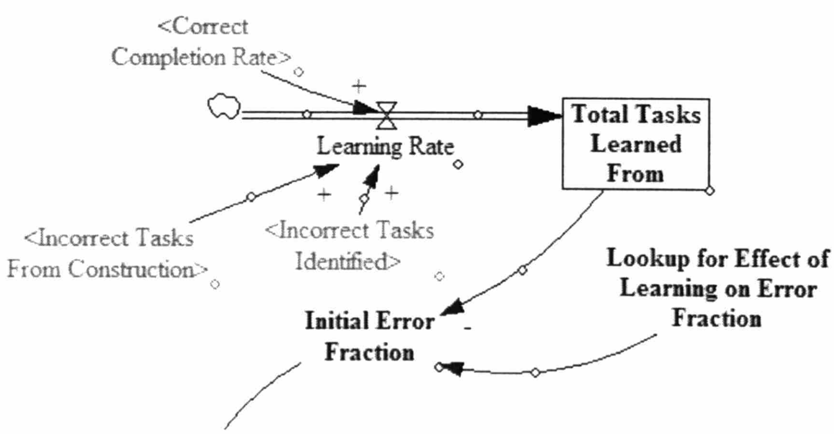
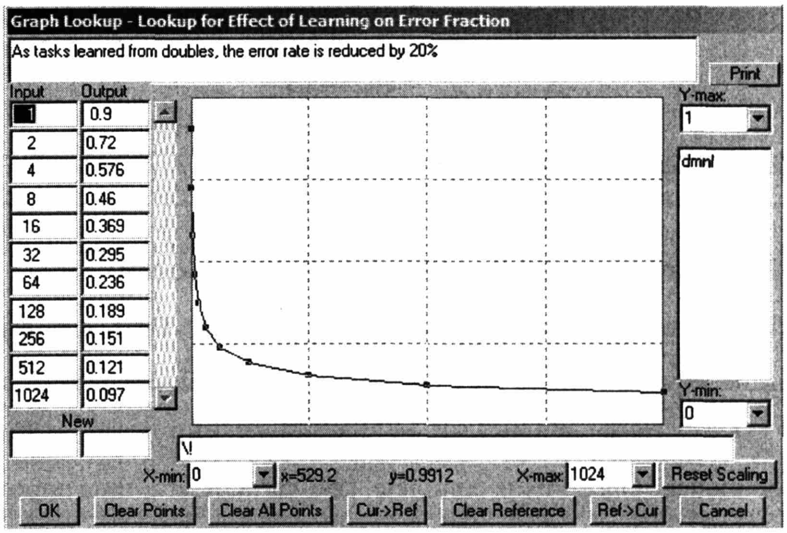


Figure 7-9 Partial System Dynamics Model- Initial Error Fraction

The Initial Error Fraction is determined by the Total Tasks Learned From (the number of tasks that A&E learns from –experience) and the Lookup for Effect of the Learning on Error Fraction. The accumulation of the Total Tasks Learned From is made up of the sum of incorrect tasks from construction, incorrect tasks identified and the correct completion rate. Below (Figure 7-10) is the graph lookup that represent the correlation between the number of tasks learned and the error fraction.



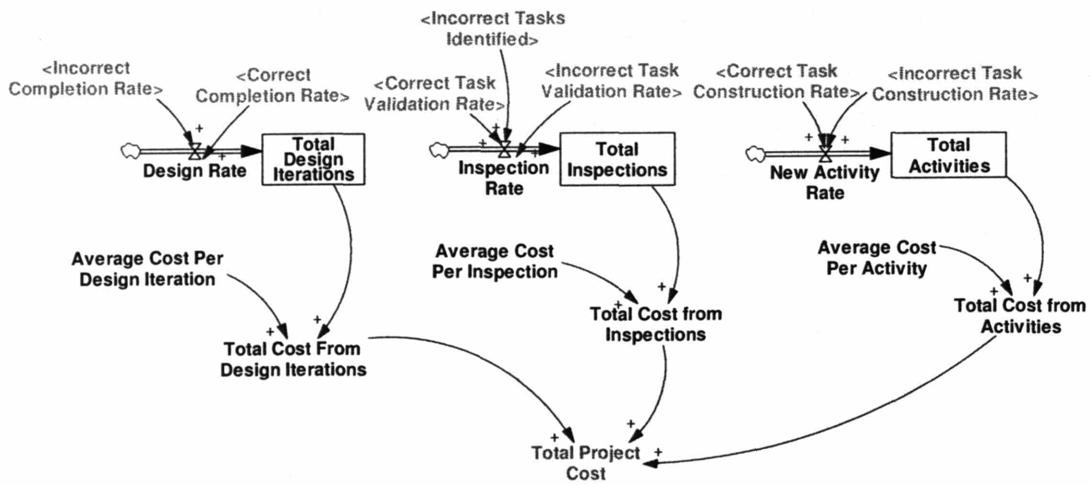
The table and graph represent a relationship between the tasks learned an error fraction. As the number of tasks are doubled the error rate reduces by 20%.

Figure 7-10 Lookup for Effect of Learning on Error Fraction Graph and Table.

Adjusted Error Fraction

Once the Initial Error Fraction and the Effect of Constructability and Design Sharing on Error Fraction have been determined Adjusted Error Fraction can be determined. Both variables have a reinforcing effect on Adjusted Error Fraction.

Financial impacts of design errors



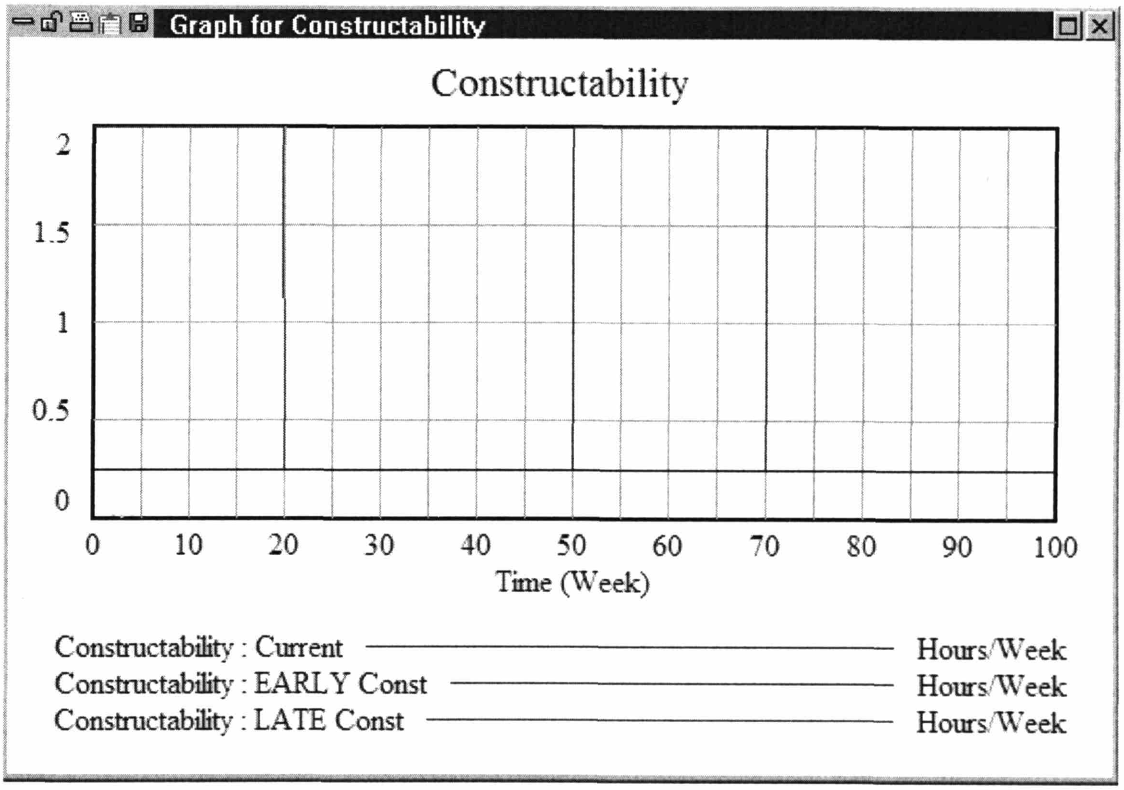
Project Completion timeline impacts of design errors

Section 7.2.2 – Analysis of System Dynamics Model

This study will use two different approaches to simulation. First, it will include a one-variable-at-a-time approach where only one exogenous variable will be changed at a time to determine the full range of implications that change will have on different internal variables in the model. Once this is complete, two-variable-at-a-time approach where the two main exogenous variables will are changed will be simulated. Results of the simulations will be compared to the current state of construction design simulation results. This will explore the true benefits and costs of the exogenous variables.

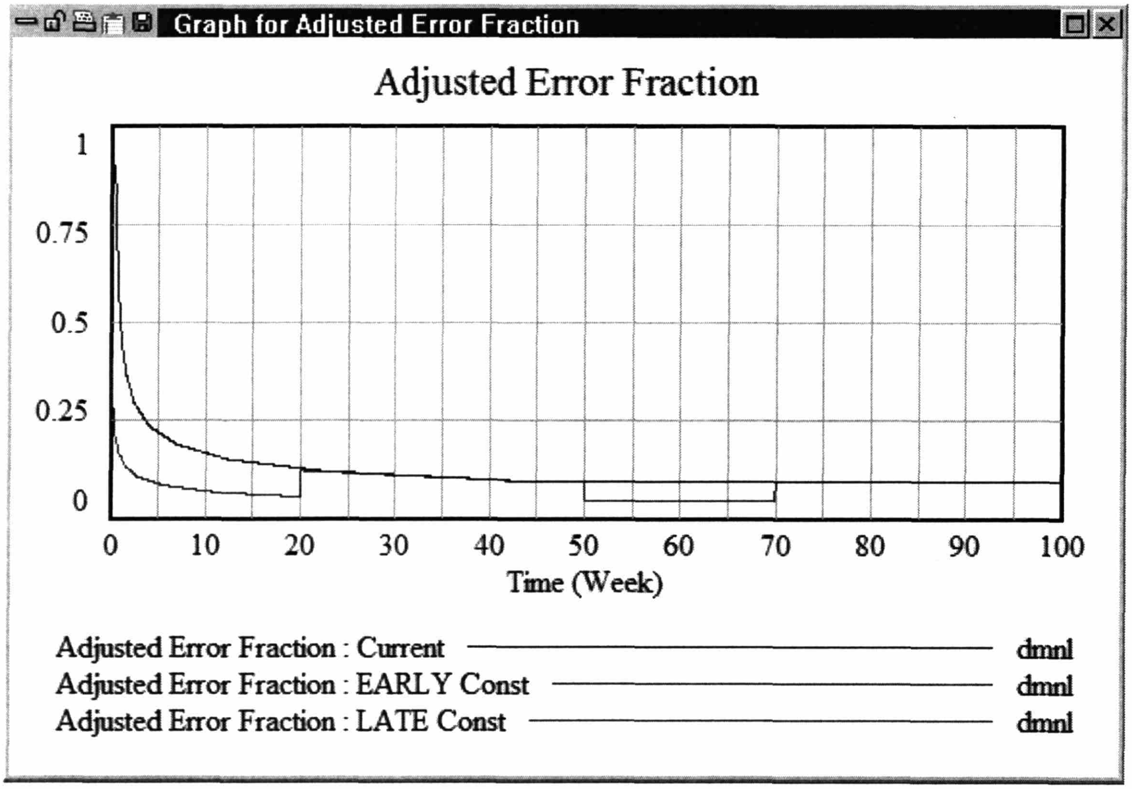
Section 7.2.2.1– Effects of Constructability

The first simulation is performed to generate results of the current state of construction design tasks (represented in blue on all graphs). Next one exogenous variable was manipulated while the other exogenous variable remained at its normal value. First the effect of early constructability was examined. An input that represented early constructability was introduced in the model. Second the effect of late constructability was examined. Current Constructability is set at .25 (2 hrs/wk) for the life of the project. Early Constructability was set to 2 (16hrs/wk) from 0 to 20 weeks and back to .25 until the end of the project. Late Constructability was set to .25 (2hrs/wk) until week 50 to 70 weeks when it was raised to 2 (16 hrs/wk) and then back down to .25 until the end of the project. The following graph shows how constructability was changed to represent early and late constructability.

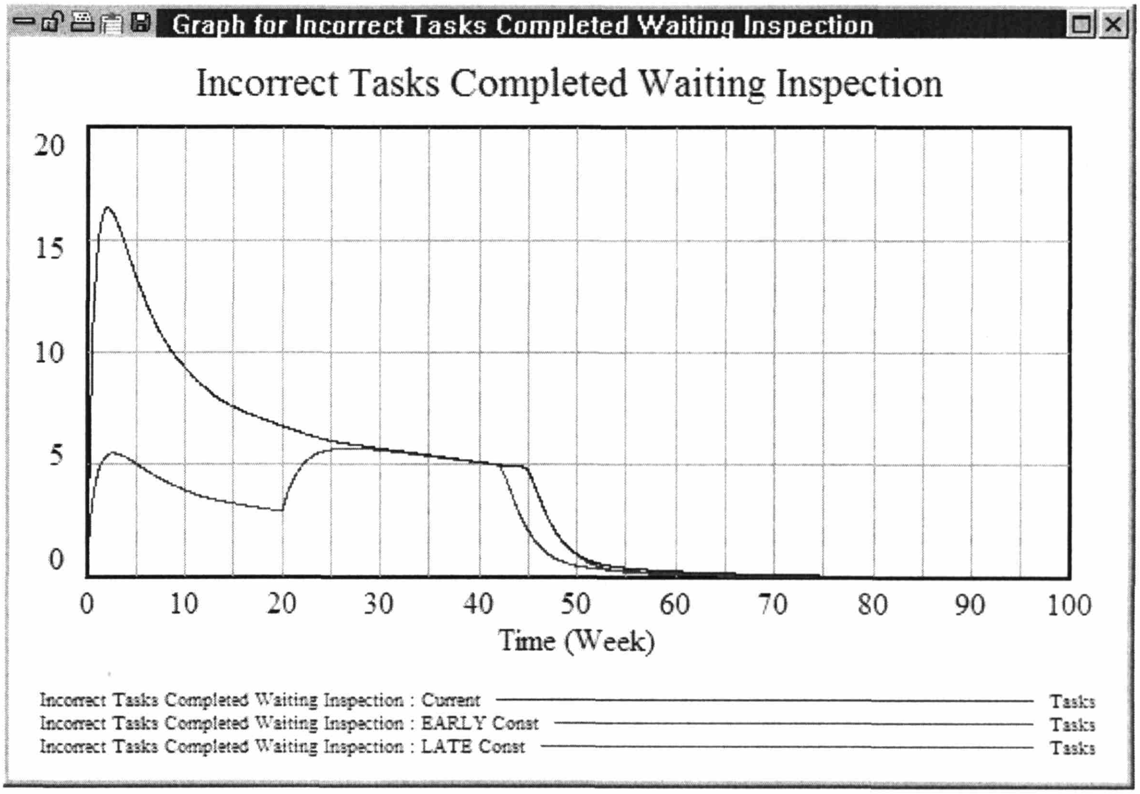


Once the changes had been introduced to the model it was important to analyze the impacts on task flow, project completion and project costs.

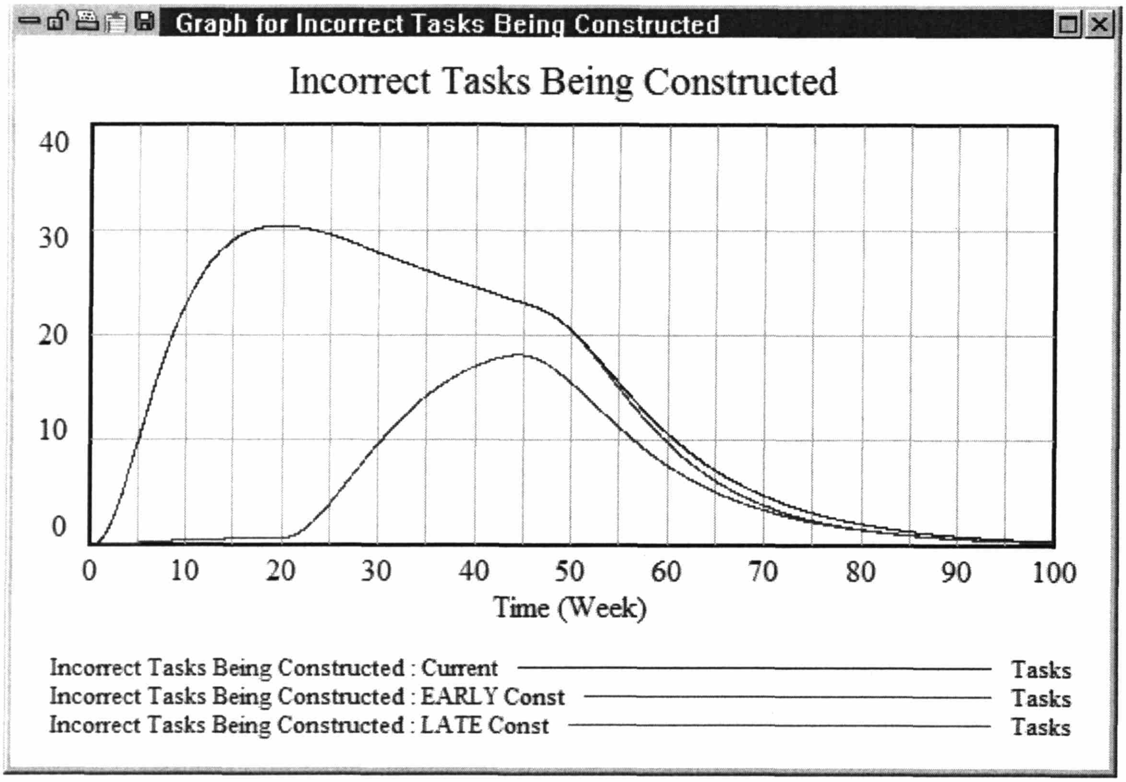
The following graph shows the effect of Early and Late constructability on Adjusted Error Fraction. As the graph shows when constructability was performed in the first 20 weeks of the project a significant drop in Adjusted Error Fraction can bee seen. Once constructability went back to .25 (2hrs/wk) the Adjusted Error Fraction increased to be equal with the current state. For the simulation when constructability was performed in the latter part of the project a drop Adjusted Error Fraction is inline with the current state and then a visible drop is seen during the time when constructability is being performed. Although, there is a visible drop in Adjusted Error Fraction it is not at the same magnitude as when early constructability is performed. Therefore, the experiment shows that early constructability has a more positive effect on reducing error fraction than late constructability.



Adjusted Error Fraction directly impacts the Incorrect Completion Rate, which has an effect on the accumulation of Incorrect Tasks Completed Waiting Inspection. This stock represents the number of completed designs that are incorrect. The following graph below shows that during the period when early constructability is performed the number of Incorrect Tasks Completed Waiting Inspection is reduced by almost 10 tasks. This seems logical because there are less errors being conducted as represented in the Adjusted Error Fraction graph above. Since the number of Incorrect Tasks Completed Waiting Inspection during the latter part of a design is already nearly zero the late constructability has not real impact.

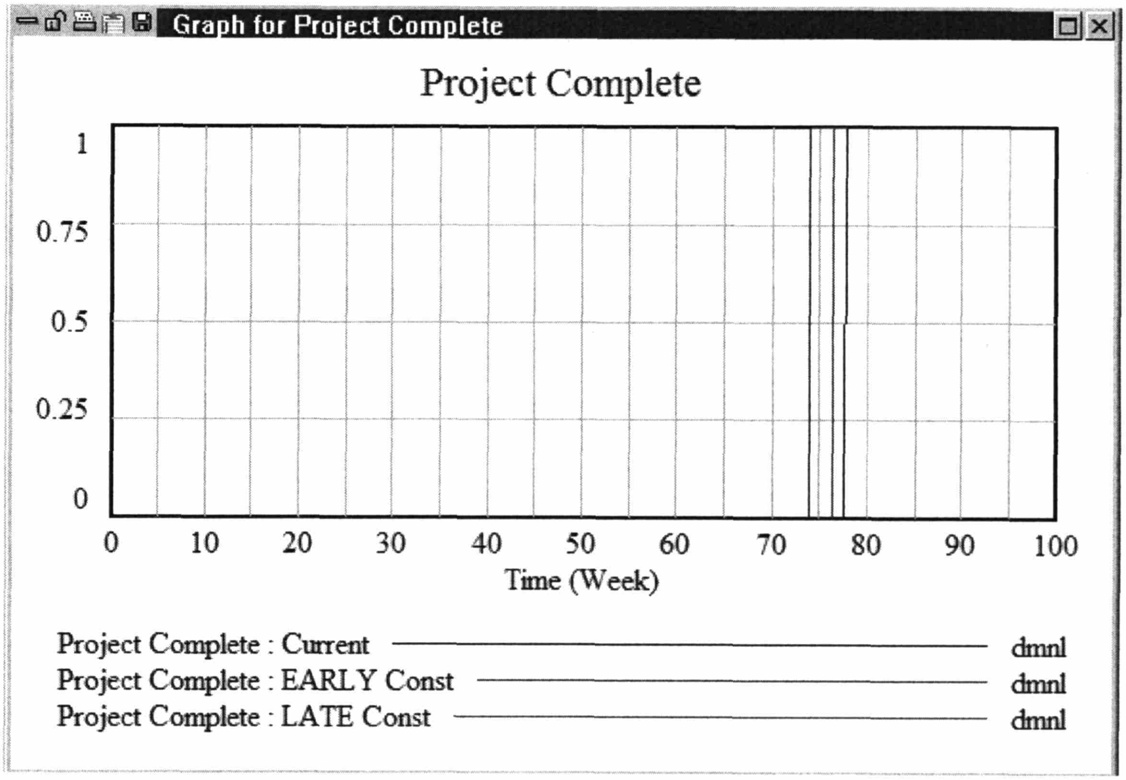


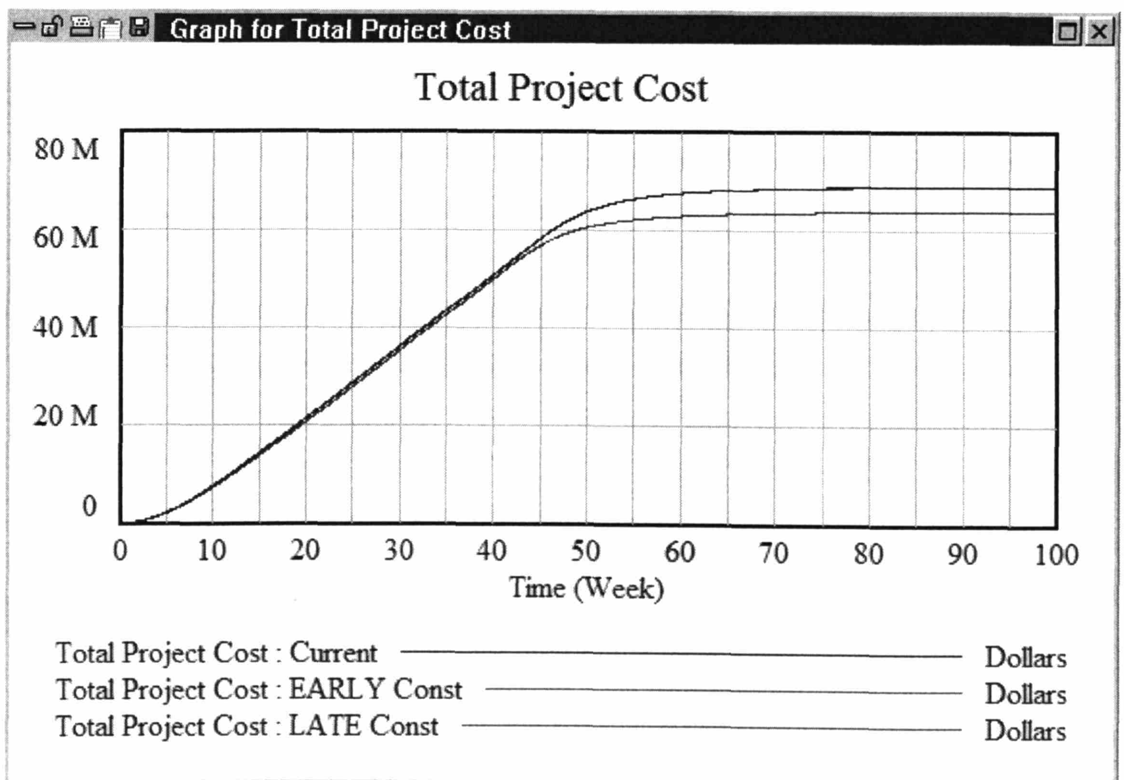
The graph below follows some of the same logic analyzed above. During the period of early constructability the number of Incorrect Tasks Being Constructed is drastically reduced, but now this value continues to remain lower than the current and late constructability tasks even after the level of constructability is reduced back to .25 (2hrs/wk).



The following two graphs show how the Project Complete date and Total Project Costs are impacted. The project completion is approximately 4 weeks shorter when early constructability (16 hrs/wk from 0 to 20 wks and 2hr/wk until the end of the project) is performed than current constructability (2 hrs/wk for the life of the project). When late constructability is performed (2 hrs/wk from start to week 50 then 16hrs/wk for 20 wks and back to 2hrs/wk until the end of the project). The project completion is approximately 1.5 weeks shorter than current constructability.

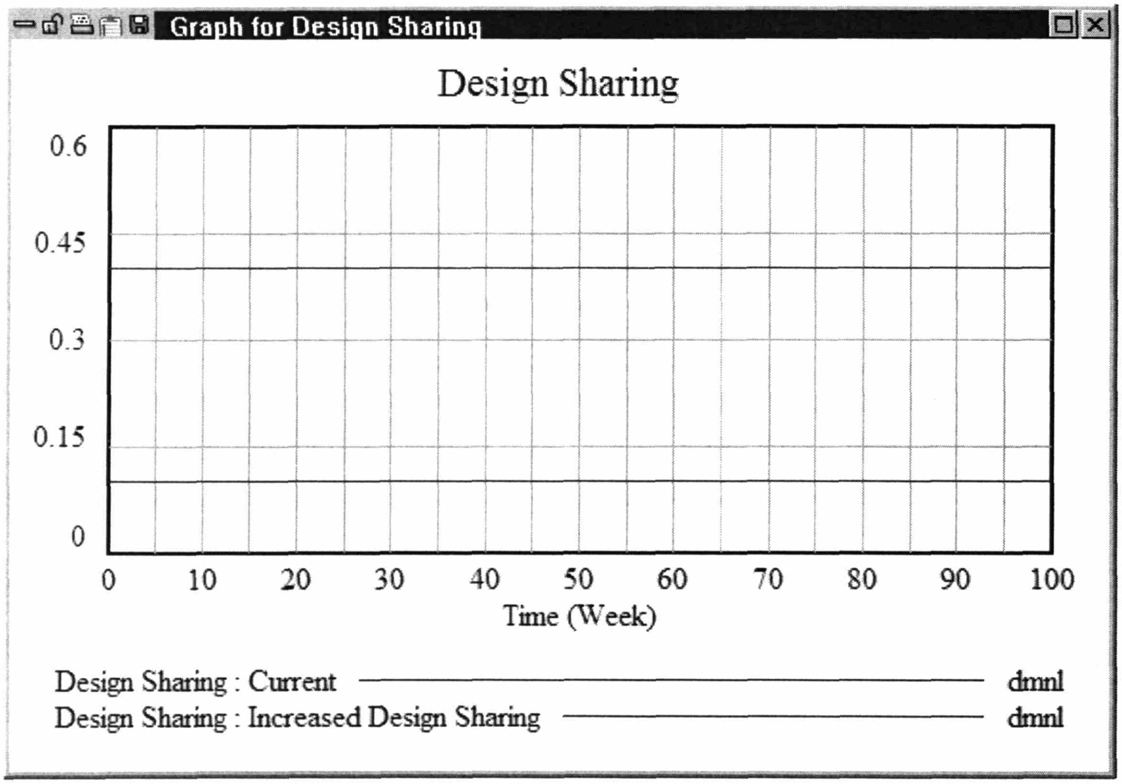
The total project costs are reduced by approximately 9% when early constructability is performed and no project costs savings occurs when late constructability is performed. Therefore, early constructability has proven to reduce Adjusted Error Fraction significantly more than late constructability and providing more favorable cost and time savings.


Graph for Project Complete
Project Complete
1
0.75
0.5
0.25
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Project Complete : Current
dmnl
Project Complete : EARLY Const
dmnl
Project Complete : LATE Const
dmnl

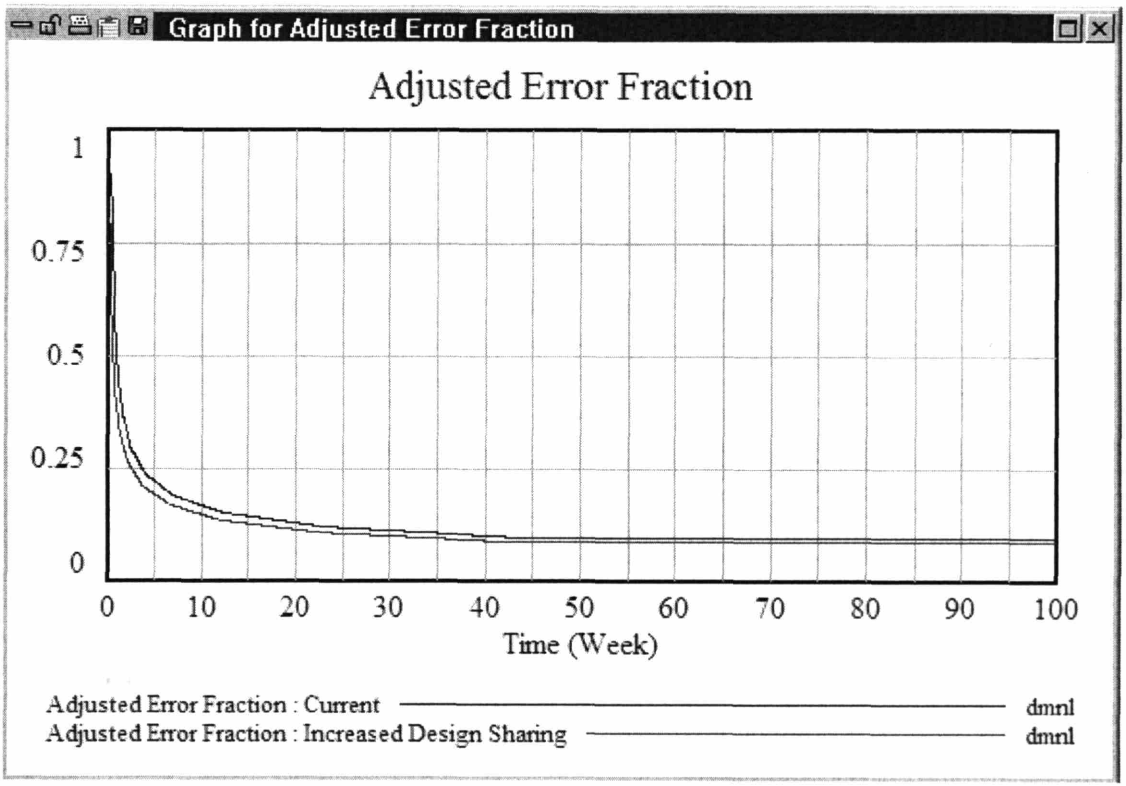

Graph for Total Project Cost
Total Project Cost
80 M
60 M
40 M
20 M
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Total Project Cost : Current
Dollars
Total Project Cost : EARLY Const
Dollars
Total Project Cost : LATE Const
Dollars

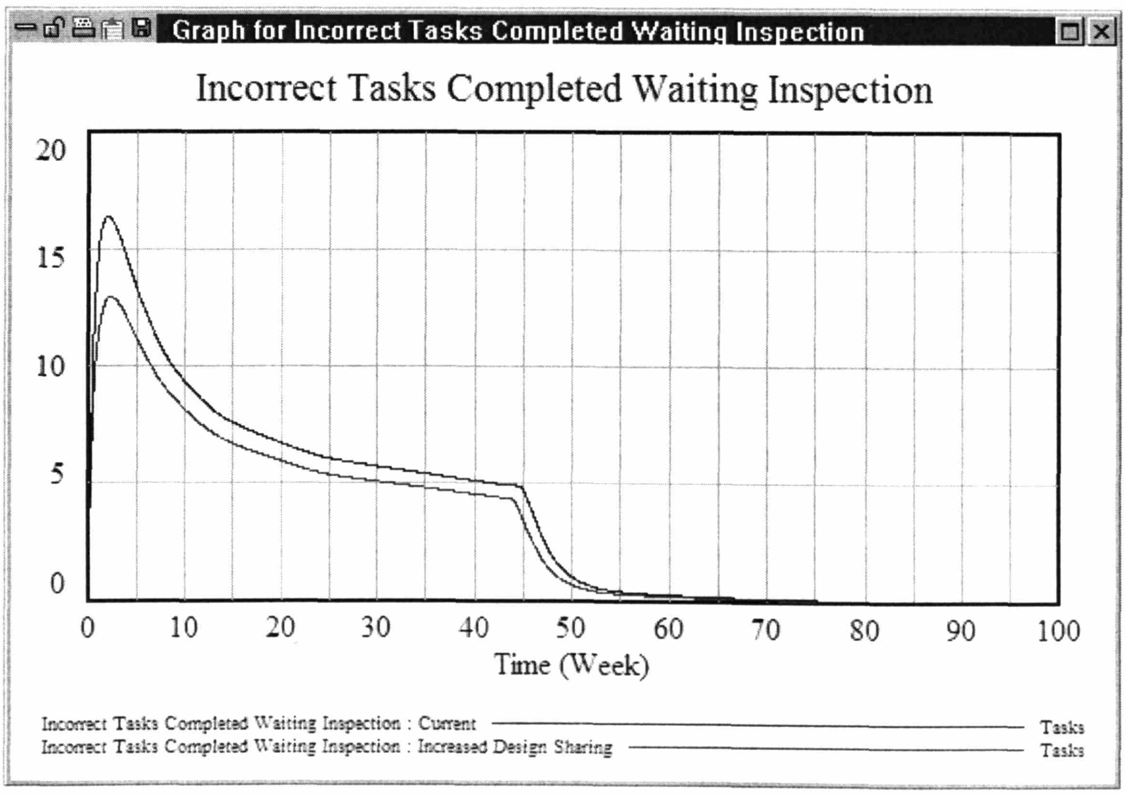
Section 7.2.2.2 – Effects of Design Sharing

The second exogenous variable Design Sharing was manipulated by increasing the value from .1, which represents traditional design sharing at 30, 60 and 90% design stage, to .4 representing an increased iterative design sharing. The graph below shows the inputs to the model.

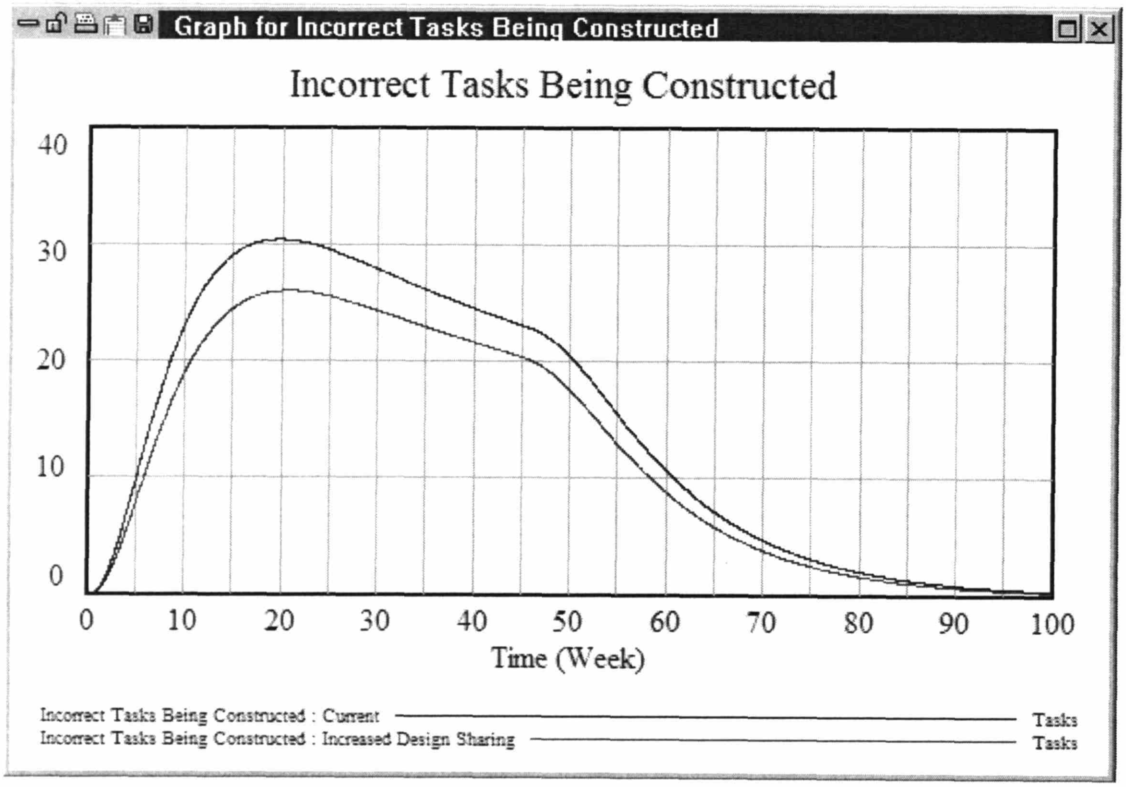


The following two graphs (Adjusted Error Fraction and Incorrect Tasks Waiting Inspection) show a marginal decrease from the increased Design Sharing.

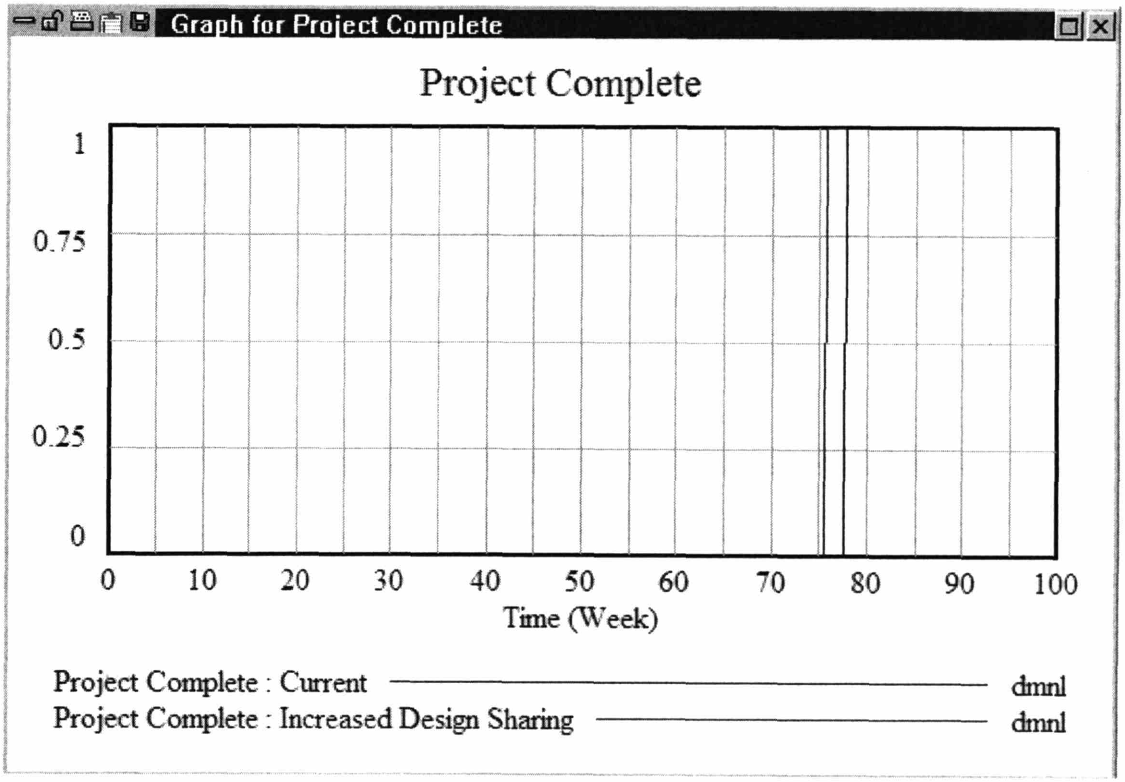

Graph for Adjusted Error Fraction
Adjusted Error Fraction
1
0.75
0.5
0.25
0
0 10 20 30 40 50 60 70 80 90 100
Time (Week)
Adjusted Error Fraction : Current dmnl
Adjusted Error Fraction : Increased Design Sharing dmnl

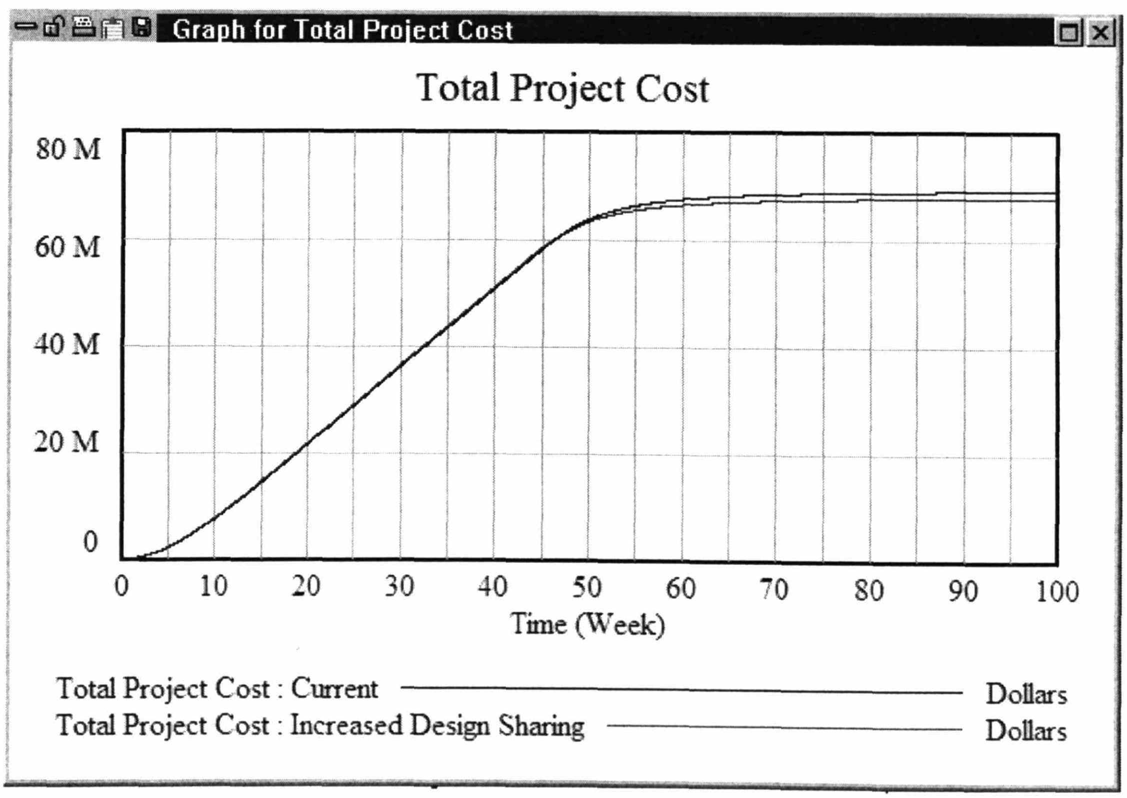

Graph for Incorrect Tasks Completed Waiting Inspection
Incorrect Tasks Completed Waiting Inspection
20
15
10
5
0
0 10 20 30 40 50 60 70 80 90 100
Time (Week)
Incorrect Tasks Completed Waiting Inspection : Current Tasks
Incorrect Tasks Completed Waiting Inspection : Increased Design Sharing Tasks

Although their was a marginal decrease in Adjusted Error Fraction from the increased Design Sharing, the number of Incorrect Tasks Being Constructed still reduced moderately from weeks 10 to 50.



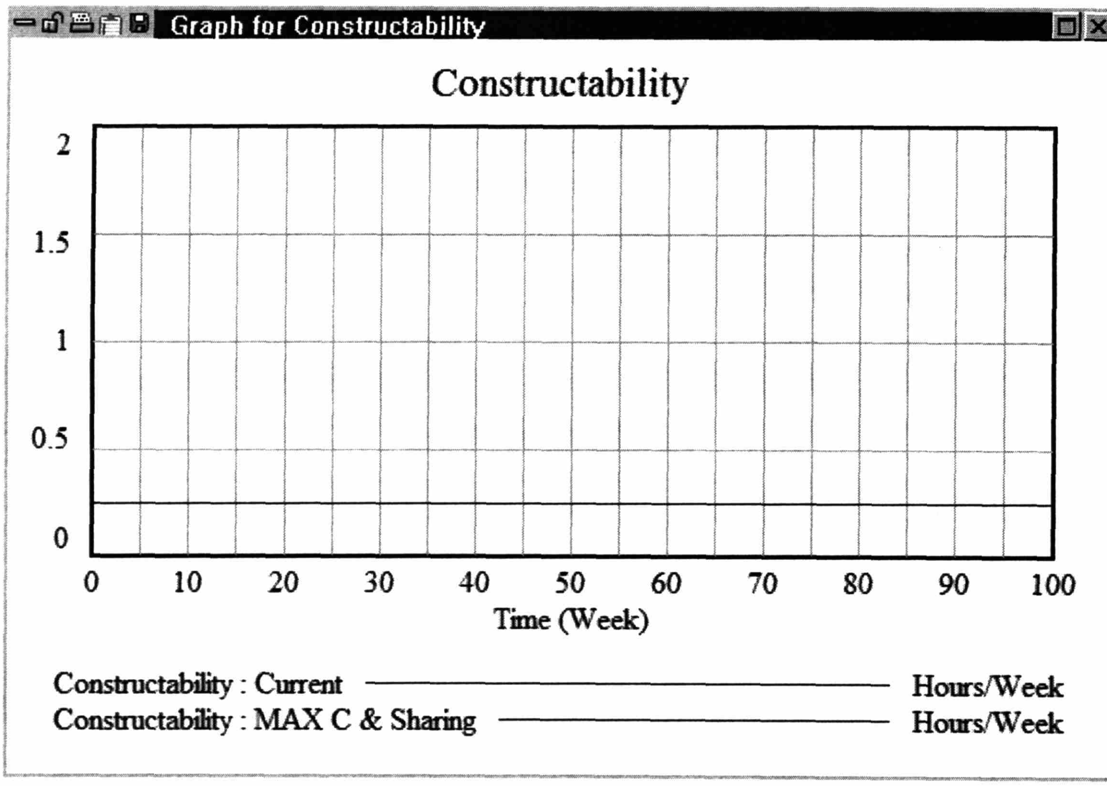
The reduced incorrect tasks being constructed caused a reduction in project completion by approximately 2.5 weeks. Total Project Costs reduced by approximately 2% with the increased Design Sharing. Therefore increased Design Sharing had a marginal reduction in Adjusted Error Fraction leading to small reductions in Total Project Costs and Project Completion.

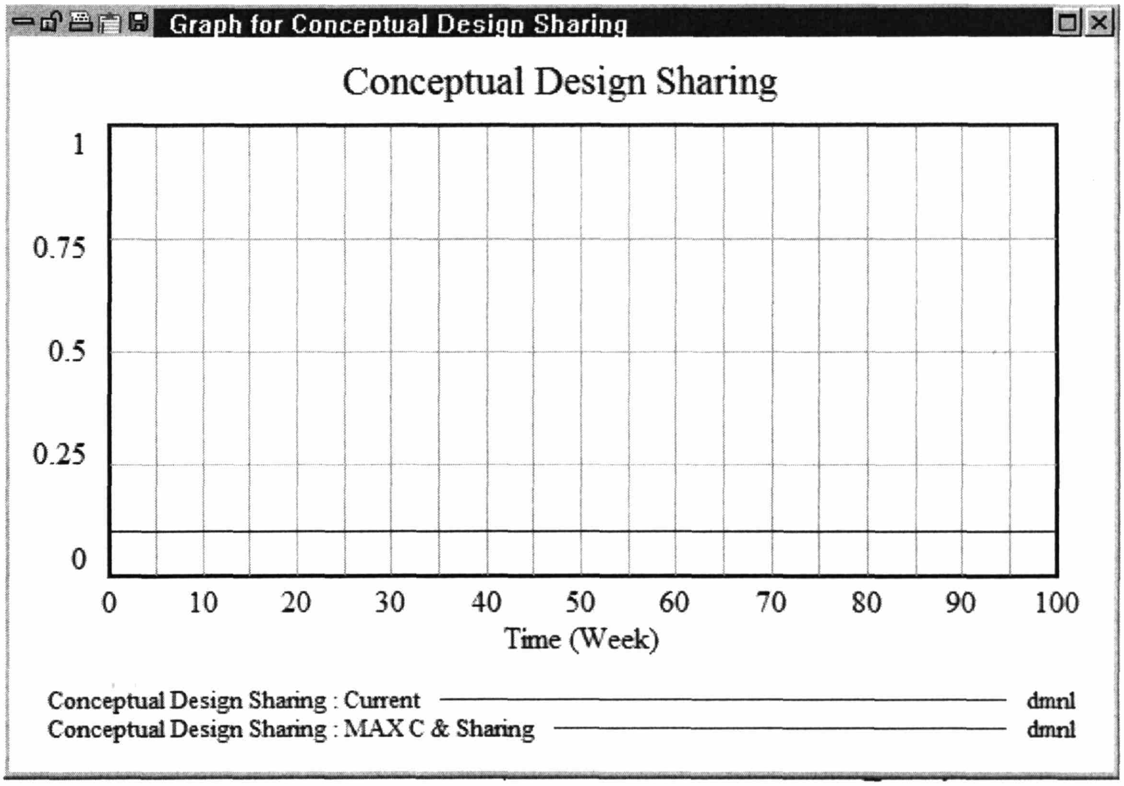

Graph for Project Complete
Project Complete
1
0.75
0.5
0.25
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Project Complete : Current
dmnl
Project Complete : Increased Design Sharing
dmnl


Graph for Total Project Cost
Total Project Cost
80 M
60 M
40 M
20 M
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Total Project Cost : Current
Dollars
Total Project Cost : Increased Design Sharing
Dollars

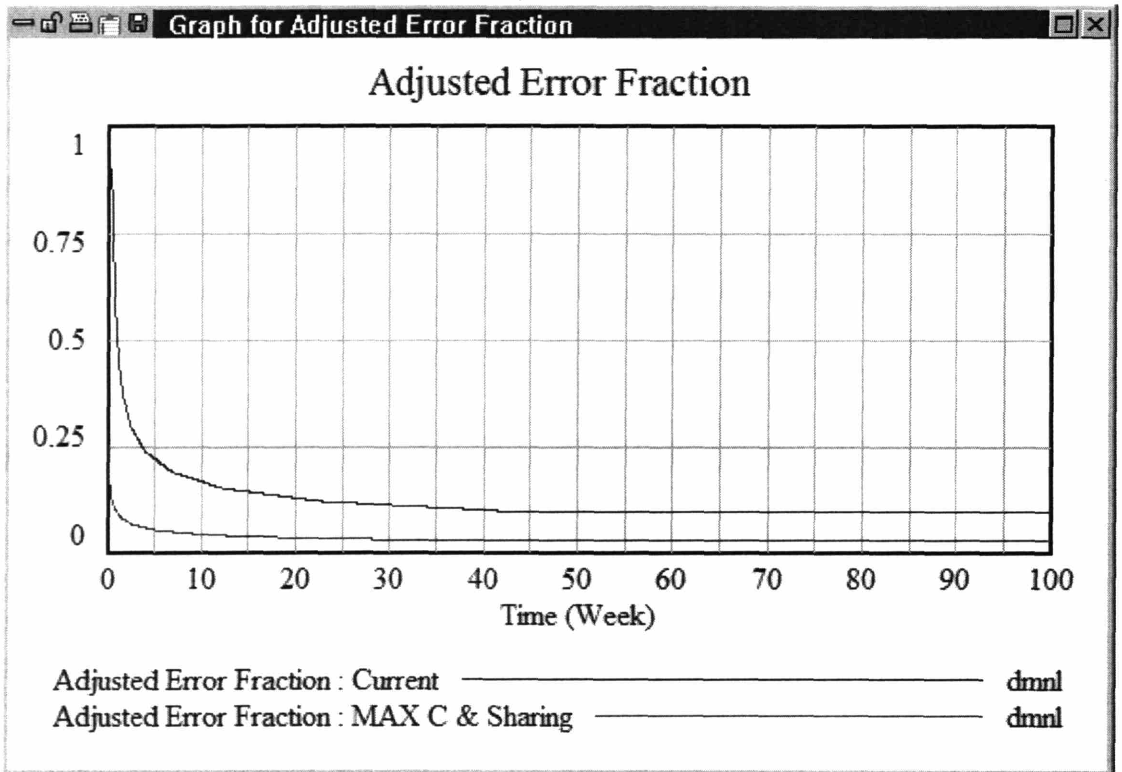
Section 7.2.2.3 – Effects of Constructability and Design Sharing

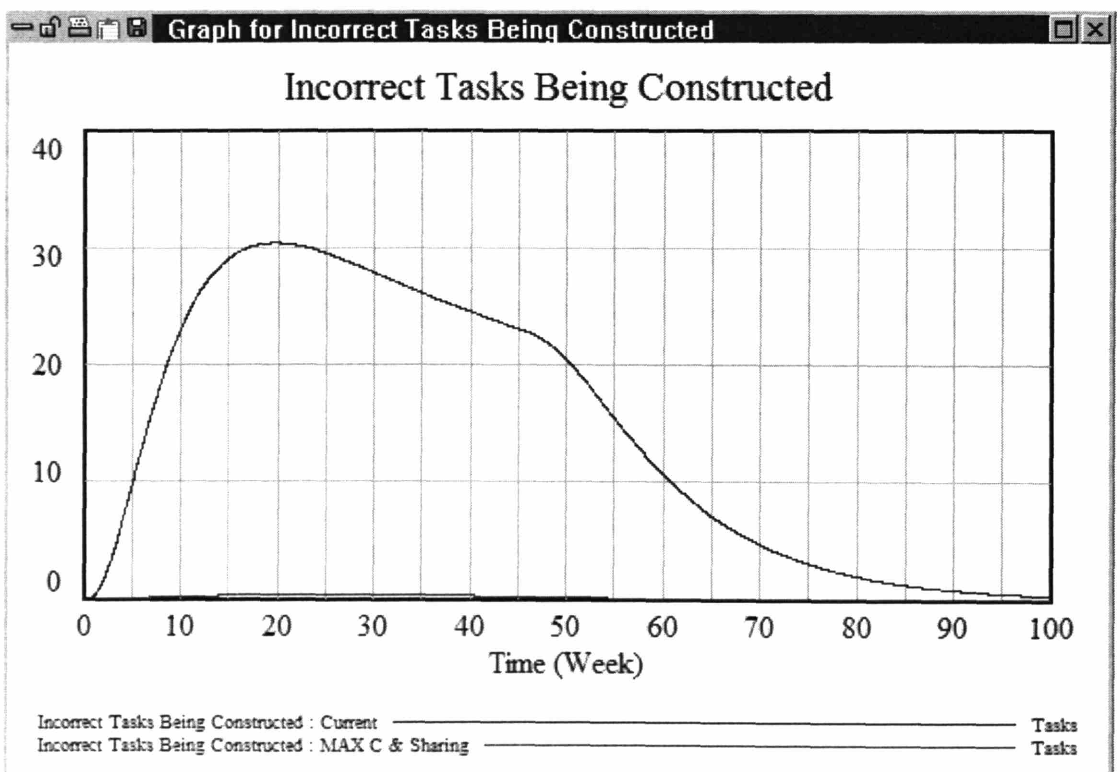
After using the one-at-a-time method for manipulating the exogenous variables Constructability and Design Sharing, both exogenous variables were manipulated at the same time. Constructability was set to 2 which represents 16hrs/wk for the entire life of the project. Design Sharing was set to 1 which represents a continual design sharing for the life of the project. The following to graphs represent the changes in both exogenous variables.

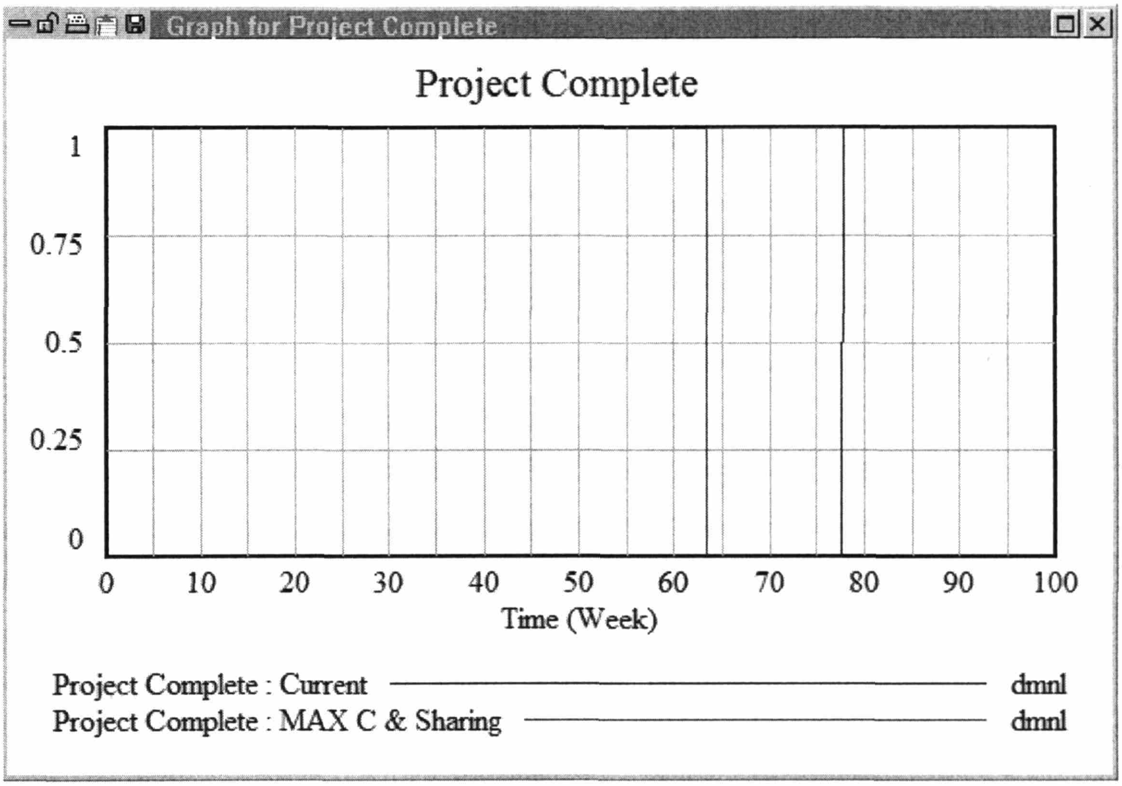


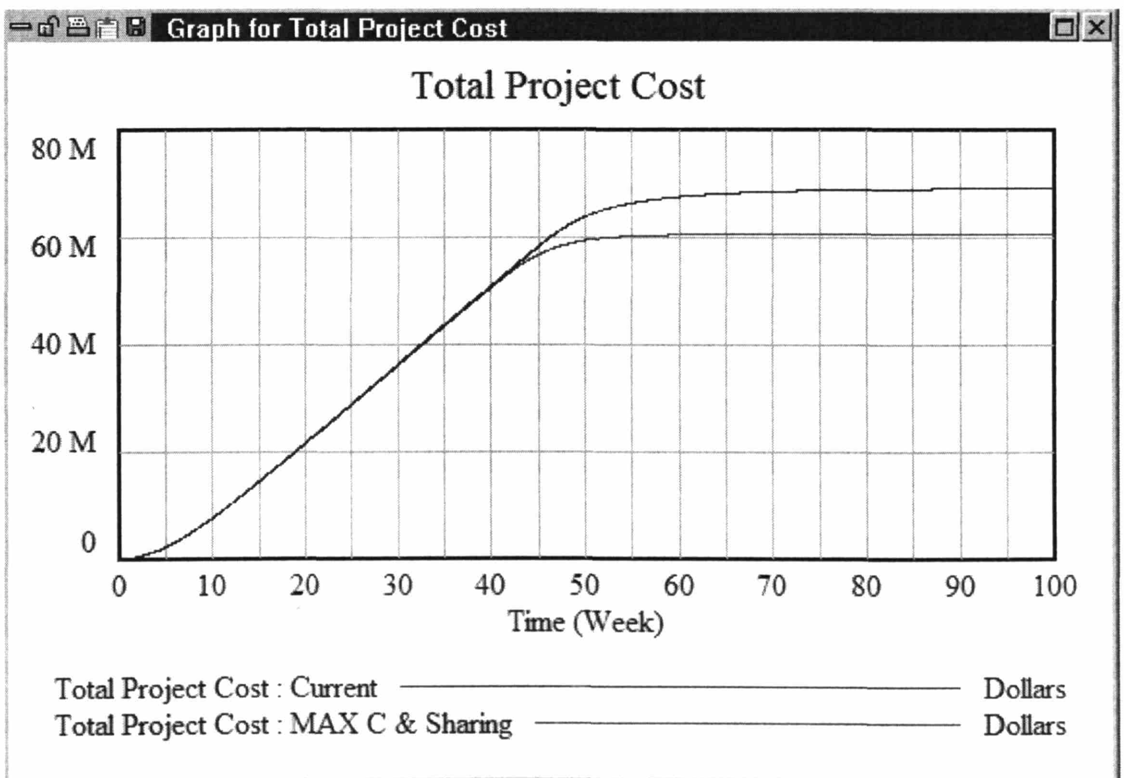


The following four graphs show the positive impacts that having maximum constructability and design sharing have on a construction project. As expected the Adjusted Error Fraction was drastically reduce for the entire life of the project leading to a significant reduction in Incorrect Tasks Being Constructed. Having less Incorrect Tasks Being Constructed reduced the total project completion by approximately 10 weeks and a Total Project Costs savings of approximately 14 % ($10M).


Graph for Adjusted Error Fraction
Adjusted Error Fraction
1
0.75
0.5
0.25
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Adjusted Error Fraction : Current
dmnl
Adjusted Error Fraction : MAX C & Sharing
dmnl


Graph for Incorrect Tasks Being Constructed
Incorrect Tasks Being Constructed
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Incorrect Tasks Being Constructed : Current
Tasks
Incorrect Tasks Being Constructed : MAX C & Sharing
Tasks


Graph for Project Complete
Project Complete
1
0.75
0.5
0.25
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Project Complete : Current
dmnl
Project Complete : MAX C & Sharing
dmnl


Graph for Total Project Cost
Total Project Cost
80 M
60 M
40 M
20 M
0
0
10
20
30
40
50
60
70
80
90
100
Time (Week)
Total Project Cost : Current
Dollars
Total Project Cost : MAX C & Sharing
Dollars

CHAPTER 8: Design Optimization

Section 8.1 – Design Optimization Introduction

The challenge of product development in the building construction industry, in a scenario of increased competitiveness, demands many companies to make a continuous effort to develop new methods in which the design for quality, cost, constructability, and reliability play an important role. In this section an analysis of how design optimization has been previously achieved will be presented.

Section 8.2 – Factors Impacting Design Optimization

First of all, the absence of a process flow notion and of a "pulled process" as exits in the lean thinking context, results in the design process being seen exclusively as a sequence of conversion activities in which individual solutions are gradually elaborated changing hands successively, in a sequential manner. Each designer is seen as a creator or "individualized" solutions are added on top of each other. Therefore the information flow is not continuous, in contradiction to what it should be according to lean thinking.

Second, the rationale underlying project development systems implies a "contract management" attitude in which an integrated vision of design/execution phases does not exist, and the focus of the activities are not centered on the customer, either it is the contractor or the final customer. What is evident is a continuous negotiation of responsibilities and duties, and the concept of value, how it is generated and how it meets the expectations of the customer, are not clearly delineated. As a result of this rationale there are no formal mechanisms or model which allow the understanding of the expectations of the customer, that is, the task of converting these expectations into design technical specifications is not carried out in a systematic manner.

Consequently as the above two points do not show how value is added in each phase of design the following design problems are common:

- Part of the requirements of the customer are "lost", or are not even take into consideration in the beginning of the design

- Part of these requirements are lost during design drafting
- There is no optimization of several solutions
- There is a lack of compliance with quality standards.

From an operational standing point, both the experience of the professional in the field and an analysis of the literature, point to some critical failures. Among them, some factors stand out[36]:

- Designs are incomplete and need additional specifications or, what is more common involve "improvisations" at the site
- Many times the deigns are not clear or explicit
- Design changes are frequent, partially due to the lack of mechanisms that allow designers to understand, in the early phases of the project, the real expectations of the customer. The duration of the design drafting stage is prolonged often making unattainable some constructive solutions due to the lack of interaction between the agents involved in the process.
- Lack of coordination among the subjects involved, which leads to the incompatibility and conflict between distinct designs.
- When considered in terms of cost, the constructive problems resulting from design failures make up the largest category.
- And finally, the cost of the design is only reduced at the expense of quality.

Faced with these problems, the reasoning structure underlying lean design proposes the use of design elaboration strategies that simultaneously embody the principles of "flow management", as pointed out by Koskela, and the management of value, and how it is created and transmitted in each one of the design phase.[37] These make it possible to establish guidelines concerned with the task of translating customer's expectations into design targets, in which constructability and reliability play an important role.

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[36] Ballard, G. "Improving Work Flow Reliability". Proc. Seventh Annual Conference of International Group for Lean Construction (IGLC-7), Berkeley 1999.
[37] Koskela, L. "Management of Production in Construction; a Theoretical View". Proc. Seventh Annual Conference of the International Group for Lean Construction (IGLC-7), Berkeley, 1999.

In this context the present work points to a procedure conceptually based on lean thinking principles that focuses on the coordination of the different design disciplines, thus avoiding errors due to the lack of design compatibility caused by inadequate management of information flow. Additionally, a design protocol is developed, helping the designers to outline constructability guidelines, applied to the specific conditions of a project . The procedure is based on the application of failure analysis methods, namely FEMA (Failure Modes and Effects Analysis), adapted from manufacturing industries design review methods, to be used in building construction design.

Section 8.3 – Design Coordination

One of the lines of action in the development of lean design, called "flow view"[38] (Ballard and Koskela, 1998), implies establishing design planning and execution mechanisms which make it flow and be pulled. One of the resources employed is the Last Planner method which has been progressively used in design management (Ballard, 1999). The adoption of methods that ensure design plan reliability, as well as reduction of variability in the information flow during the execution of design tasks is not a guarantee, *per se,* that this flow represents the best way of interaction among designers during design development. In this way, a second action line implies developing procedures and a design protocol that leads to:

- A clear definition of the stages of the design.
- The establishment of multi-functional teams which work since the early stages of the project.
- A definition of the documents and of the information which need to be available in the beginning of the design.
- The introduction of mechanisms which allow the logical concatenation of information among the intervening agents.[39]
- The establishment of methods and techniques of design co-ordination by adopting interaction guidelines by the designers involved.

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[38] Ballard, G and Koskela, L. "ON the Agenda of Design Management Research". Proc. Sith Annual Conference of the International Group for Lean Construction (IGLC-6) Guruja, Sao Paulo, 1998.
[39] Fabricio, M., Melhado, S and Baia, J. "Brief Reflection on Improvement of Design Process Efficiency in Brazilian Building Projects". Proc. Seventh Annyak Conference of the International Group for Lean Construction (IGLC-7), Berkeley, 1999

Faced with these challenges, the objective of the method presented below was to establish technical guidelines for the several designers involved (architects, structural calculation staff, electrical installation and telephony designers, etc.) as checklists containing potential incompatibilities among the several designs, and the preventive actions for these incompatibilities. In this way, a communication protocol was created for sharing technical specifications.

Another aspect that should be considered is that it is necessary to set up design procedures that assure that the customer's expectations are considered during the successive phases of the design process. In this light, two dimensions of value might be considered:

1) The technical characteristics of the building which actually meet the customer's expectations, including the constructive solutions detailed in the executive design

2) The design specifications would imply eliminating uncertainties, rework and makeshift solutions during the execution, leading to an increase in constructability.

For this, the establishment of a procedure which implies preventing incompatibilities among the distinct designs will make possible, on the one hand, the absence of constructive problems which affect negatively the quality characteristics of the building, and, on the other hand, it will imply the increase of the constructability. The design co-ordination procedure proposed was developed in this context.

Section 8.4 – Proposed Procedure Steps

First step: Establishment of a checklist containing the tasks of the distinct designs

Initially, a checklist containing all the activities of the design are drafted. This includes the activities which must be carried out, from pre-design to the detailing of the executive design.

Second step: Refinement of the checklist

Once the checklist has been drawn up, it is refined, that is, the activities which are not expected to bring up interference problems with the other designs or critical constructive solutions concerning ease of execution were eliminated, either because of their objective, or because the design standards had already anticipated, in such cases, possible interferences.

Third step: Drawing up correlation matrices among the design activities.

Once the items of each design to be taken into consideration have been determined, correlation matrices are developed pairing up the elements of one design (for instance the architectural design) with all the others (for instance, structural).

Fourth step: Analysis of the correlation matrices

In the next step, the matrices are analyzed, assigning weights to the several lines and rows. The analysis allows the team members to select the items which are considered most critical, and which will be the object of the FMEA analysis. That is, the analysis of the matrix works as a first "filter". This allows the team members to consider the critical activities that will be the object of design recommendations.

Fifth Step: FMEA analysis

A failure modes and efforts (FEMA) analysis is performed for each critical activity of the design, selected from the correlation matrix, considering the potential interferences with the specifications of other designs.

Sixth Step: Drawing up a checklist with constructive recommendations

For the activities with a higher risk index in FMEA, preventive actions and guidelines are listed that prevent compatibility problems with other designs and imply the optimization of the constructive processes.

Part III – LEAN THINKING APPLIED TO CONSTRUCTION DESIGN

CHAPTER 9: SUMMARY CONCLUSIONS AND RECOMMENDATIONS

This thesis reviewed the influence of the design stage on the outcome of construction projects both technically and economically. It reviewed the current state of the construction industry, lean practices and success in manufacturing, major problems in construction design, value of computer integrated construction and recent research in lean construction. The findings in this study reinforce the fact that changes early in the life of project have a more beneficial impact then changes later in a project.

Additionally the findings suggest the importance of a full life-cycle approach for developing a lean design environment. More significantly, designers and constructors can implement lean based design through a process that focuses on creating flow in the value stream. In this manner, lean based design is consistent with previous investigations on the constructability concepts. Although the inspiration and objectives of initial constructability research and lean production vary, the initial findings are relevant when considering a full life cycle design led lean approach.

The system dynamics model developed has demonstrated the dynamics of design collaboration through constructability reviews and design sharing. Although this version of reality may not capture the mass of complexity, the model presented in this paper can enable design and project managers to better understand the process of construction design and how design errors occur in construction project. To reduce the likelihood of design errors occurring in a project, practitioners need to have mechanisms that promote collaboration between the A/E and construction contractors.

Section 9.1 – Conclusions

Historical resistance by the construction industry to accept ideas from manufacturing has limited the acceptance and use of lean construction. The traditional transformation view of construction is contrary to lean principles, which shift the focus from craft production to the overall process (including design). The goal of lean construction is to make value-added activities flow, which can only be accomplished if lean concepts are included from the very beginning of the design process.

Lean Design can be accomplished by considering constructability in the design in order to improve flow at the job site. This can only be accomplished by collaborative decision making with the A/E and subcontractors. Design and should be selcted to enable efficient construction operations, this can only be accomplished through collaboration and constructability validation. Traditional constructability concepts developed in the 1980s still apply to lean construction and can be enhanced through the consideration of how to make the process flow. Standardization of design elements, modularity, and pre-assembly are all methods that can improve flow on the construction job site.

In addition to consideration of constructability concepts, design teams must be expanded to include contractors, subcontractors, and materials suppliers. Communication among all parties will be difficult; however, advances in information technology are making it easier to communicate. Through universal access, all key players can work cooperatively on a design instead of isolated from each other. With increased cooperation and collaboration, it is not difficult to incorporate lean principles into construction practices. But, with the development of Information Technology and Building Information Modeling most obstacles are easily mitigated.

To conclude, the implementation of lean design requires a radical shift from traditional construction methods. The benefits, however, far outweigh the initial costs by creating a process dedicated to pursuit of perfection.

Section 9.2 – Recommendations

A fundamental aspect that is necessary to emphasize is the necessity of creating awareness about the concepts of Lean Principles as they apply to Lean Design in the construction industry. People generally do not know the principles involved in Lean

Design and tend to work according to their habits, fundamentally based in the traditional conversion model. Furthermore, they have not questioned how this standard works nor if alternative methods are available to manage the design process. In this manner, the focus on flow and generation of value provides an important complement to support the understanding of the process. This means that tools and methods that support Lean Design concepts and principles must be introduced and applied.

The following is a proposed conceptual framework as a result of the synthesis of material discussed in both the literature review and analysis sections of this study. The underlying sets of ideas are to promote a systemic lean approach to construction design. There are four main parts to the framework; Contractual Relationship, Collaborative Design Sharing, Constructability Validation, and Information Technology. See Figure 9-1 for a graphic representation. The four parts of the framework are integrated together and supported by a contractual relationship. Although, ideally design and construct teams would not need a contract specifying their requirements or commitments, but real work problems have proven that these relationships need to me formal to be valid.

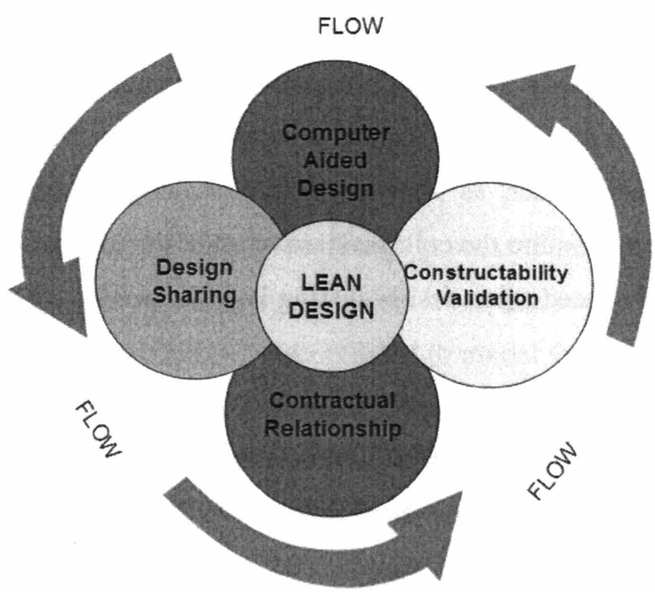


Figure 9-1 Lean Design Framework

Contractual Relationship

Design and Construction entities on a project need to be organized in such a way that they all function as a single company with a single goal with no competition amongst them for profit or recognition. Therefore each member of the design build team shares completely the responsibility for the entire project. Also the team jointly sets about correcting deficiencies or problems whereever they pop up without regard to who caused the problem or who is going to pay for the damages. If all stakeholders share the responsibilities and the rewards innovative design solutions will be shared.

Constructability Validation

The separation of the design and construction phases in projects makes it difficult to create flow in the overall process. Because the A/E industry views design as a distinct process with its own product, there is little incentive to spend time and money on constructability issues. The system dynamics model has shown that constructability in the early stages of design will reduce the number of errors, time and money in a construction project. Therefore, the framework has included the need for constructability validation from all contractors and subcontractors as one of the four factors.

Collaborative Design Sharing

Only through collaborative design sharing amongst A/E can design optimization be accomplished. Benefits such as standardization of design elements to be used to minimize cost and time require the collaboration of all design disciples. The reduction in design errors is also reduced when design sharing is performed.

Computer Aided Design

Two of the three case studies discussed in this study demonstrated that computer aided design such as Building Information Modeling reduced the number of RFI's, cost over runs and time on a construction project. BIM promotes collaborative sharing of information and design validation.

Section 9.3 – Summary

In Part I, Background and Literature Review, this study started by discussing lean as it is applied to the manufacturing industry. Fundamental lean principles were presented along with the Toyota Production System, where the principles originated. Next the current state of design in the construction industry was explored. This exploration brought to light major problems in current construction design processes; the lack of consideration for flow processes in construction allows a significant amount of waste, loss of value and non value added activities. These wastes along with contractual relationships that don't promote the sharing of innovative solutions create unnecessary negative iteration. A common finding in the literature review was the lack of collaboration amongst the A/E and the general contractor and sub-contractors during design. In efforts to combat these and other problems in the construction industry the Lean Construction Institute was developed. This group of people research how Lean Principles, as applied to manufacturing, can be applied to the construction industry. Their efforts show that manufacturing principles of production can be effectively applied to the construction industry. The study presented three cases where "Lean Construction" theories were utilized in design development. The results in these projects showed a phenomenal improvement in the reduction of design errors. These positive results were due to the collaborative efforts to ensure design constructability and clear communication through CAD tools.

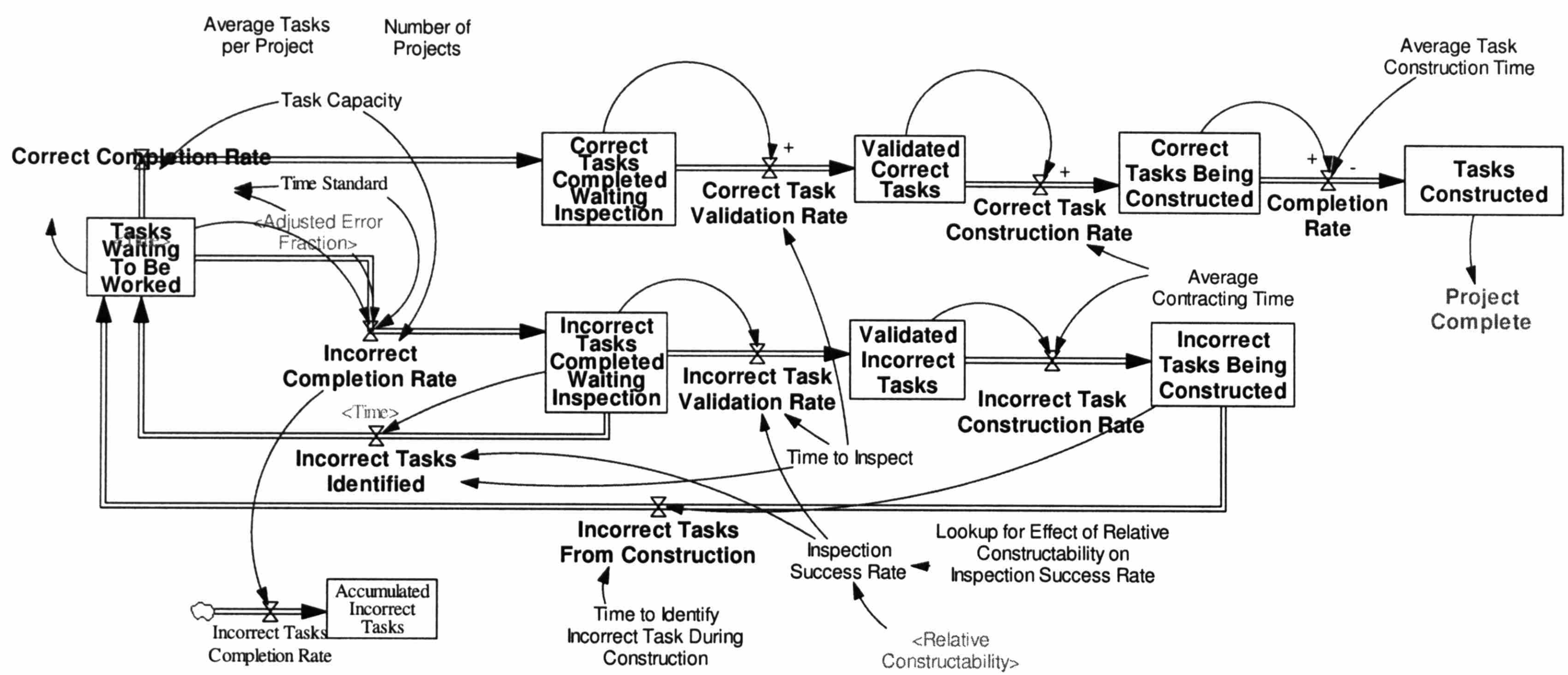
Part II presented an analysis of the current design process. First, an overview of how the major problems in construction design, which were presented in Part I, could be overcome. Secondly system dynamics was utilized to model the design process and lastly a sequential process of how design optimization could be accomplished. The findings in this section provided insight of how waste could be minimized and flow enabled. As previously mentioned above, the lack of collaboration amongst A/E's and contractors created design errors. The system dynamics model allowed the simulation of the design process and manipulation of design sharing and constructability parameters. The findings demonstrated how lack of early collaboration allowed design errors to be found during construction and not in the early stages of design. As a result, these errors were manifested into higher project costs.

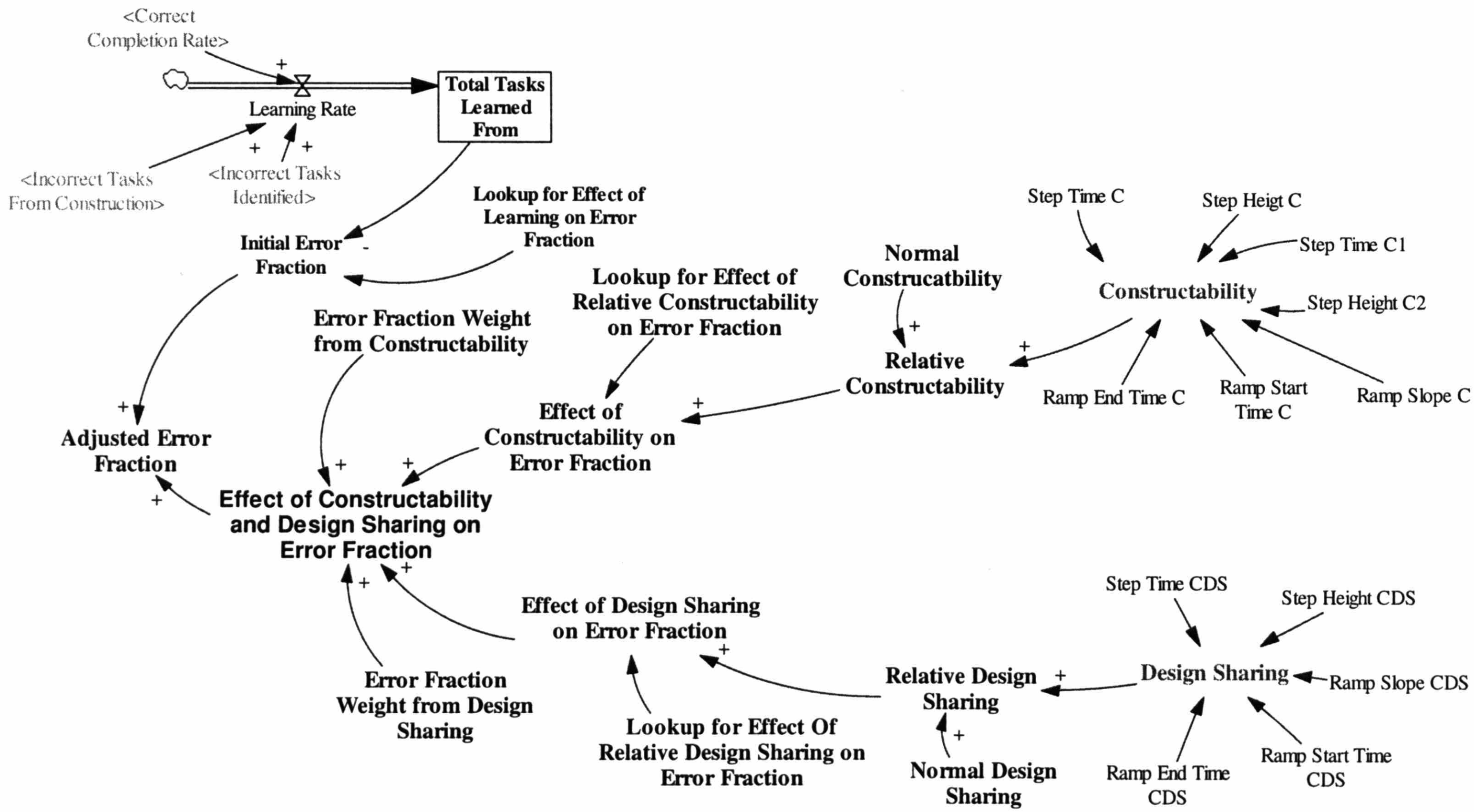
This study highlights the need for early collaboration amongst A/Es and contractors and clear communication of the designs' intent. Major problems such as one-of-a-kind production and temporary-organizations emphasize that the dynamics of construction projects and the need to have some standardization. Utilizing IT tools can help optimize designs, share knowledge and provide more efficient and constructible designs.

Appendix A: Acronyms

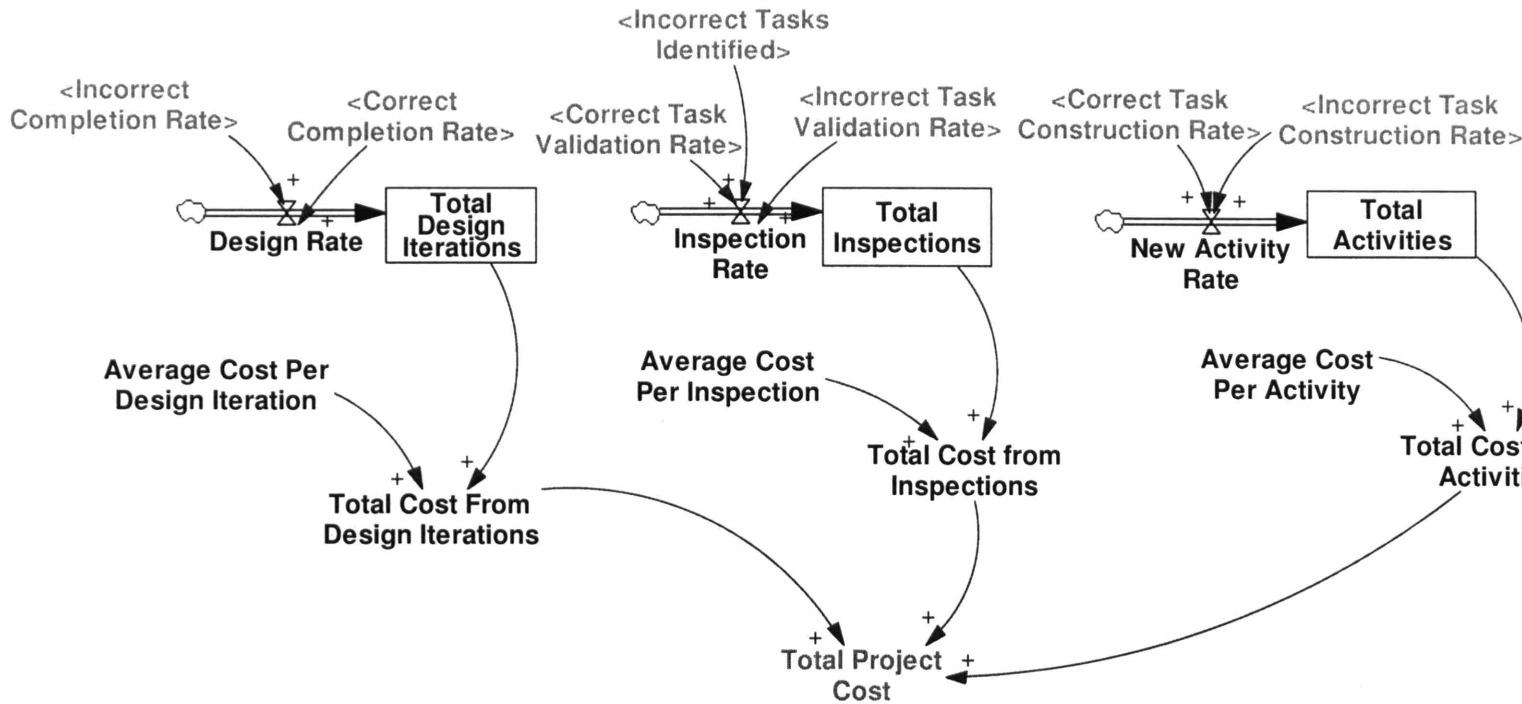
ADM	Activity Definition Model
AEC	Architect Engineer Contractor
BIM	Building Information Modeling
BOT	Build Operate Transfer
CAD	Computer Aided Design
CPM	Critical Path Method
DB	Design Build
DSM	Design Structure Matrix
FP	Fire Protection
GC	General Contractor
HVAC	Heating Ventilation Air Conditioner
IPD	Integrated Project Delivery
IT	Information Technology
JIT	Just in Time
LCI	Lean Construction Institute
LPDS	Lean Project Delivery System
LPS	Last Planner System
PPC	Percentage Planned Complete
PTM	Primary Team Members
QFD	Quality Function Development
RFI	Request For Information
T	Turnkey
TPS	Toyota Production System
TQC	Total Quality Control

Appendix B: System Dynamics Model





<Correct Completion Rate>
Learning Rate
Total Tasks Learned From
<Incorrect Tasks From Construction>
<Incorrect Tasks Identified>
Initial Error Fraction
Lookup for Effect of Learning on Error Fraction
Adjusted Error Fraction
Error Fraction Weight from Constructability
Lookup for Effect of Relative Constructability on Error Fraction
Normal Construcatbility
Relative Constructability
Effect of Constructability on Error Fraction
Effect of Constructability and Design Sharing on Error Fraction
Step Time C
Step Heigt C
Step Time C1
Constructability
Step Height C2
Ramp End Time C
Ramp Start Time C
Ramp Slope C
Effect of Design Sharing on Error Fraction
Error Fraction Weight from Design Sharing
Lookup for Effect Of Relative Design Sharing on Error Fraction
Relative Design Sharing
Normal Design Sharing
Design Sharing
Step Time CDS
Step Height CDS
Ramp Slope CDS
Ramp End Time CDS
Ramp Start Time CDS


<Incorrect Tasks Identified>
<Incorrect Completion Rate>
<Correct Completion Rate>
<Correct Task Validation Rate>
<Incorrect Task Validation Rate>
<Correct Task Construction Rate>
<Incorrect Task Construction Rate>
Design Rate
Total Design Iterations
Inspection Rate
Total Inspections
New Activity Rate
Total Activities
Average Cost Per Design Iteration
Average Cost Per Inspection
Average Cost Per Activity
Total Cost From Design Iterations
Total Cost from Inspections
Total Cost from Activities
Total Project Cost

Appendix C: System Dynamics Variables and Formulas

(01) {UTF-8}
Units: **undefined**

(02) Accumulated Incorrect Tasks= INTEG (Incorrect Tasks Completion Rate, 0)
Units: Tasks
The stock of accumulated incorrect tasks completed based on the incorrect tasks completion rate.

(03) Adjusted Error Fraction=
IF THEN ELSE(Effect of Constructability and Design Sharing on Error Fraction *Initial Error Fraction<=0.99 ,Effect of Constructability and Design Sharing on Error Fraction
*Initial Error Fraction , 0.99)
Units: dmnl
The error fraction represents the effect of constructability design sharing and the initial error fraction from tasks learned.

(04) Average Contracting Time= 4
Units: Weeks
The average time it takes once a project is validated until a contractor is hired and construction can begin, set at 4 weeks.

(05) Average Cost Per Activity= 40000
Units: Dollars/Task
The Average Cost for an Activity to be constructed.

(06) Average Cost Per Design Iteration= 5000
Units: Dollars/Task
Average fixed value for the cost of every design iteration.

(07) Average Cost Per Inspection= 1200
Units: Dollars/Task
The cost to inspect tasks downstream after design has been completed.

(08) Average Task Construction Time= 5
Units: Weeks
The average time it takes to construct a task. On average it takes 5 weeks to construct a task.

(09) Average Tasks per Project= 1000
Units: Tasks/Project
Fixed amount of tasks that represent the average amount of tasks per project.

(10) Completion Rate=
Correct Tasks Being Constructed/Average Task Construction Time
Units: Tasks/Week
The rate a which tasks are being completed, which is the ratio of correct tasks being constructed and the average task construction time.

(11) Constructability=
0.25+STEP(Step Heigt C, Step Time C)+STEP(Step Height C2, Step Time C1)+ RAMP(Ramp Slope C, Ramp Start Time C , Ramp End Time C)
Units: Hours/Week
The total amount of time spent on constructability reviews in hours per week.

(12) Correct Completion Rate=
MIN((Tasks Waiting To Be Worked/Time Standard)*(1-Adjusted Error Fraction),Task Capacity*(1-Adjusted Error Fraction))
Units: Tasks/Week
The rate at which correct tasks are completed. This is determined by taking the minimum of the tasks waiting to be worked divide by the standard time it takes a task to be completed times the adjusted error and the task capacity times the adjusted error fraction.

(13) Correct Task Construction Rate=
Validated Correct Tasks/Average Contracting Time
Units: Tasks/Week
The rate a which correct tasks are constructed, derived from the ratio of validated correct tasks and the average time contracting time.

(14) Correct Task Validation Rate=
Correct Tasks Completed Waiting Inspection/Time to Inspect
Units: Tasks/Week
The rate at which a correct task is validated, which is the ratio of correct tasks completed waiting for inspection and the time to inspect.

(15) Correct Tasks Being Constructed= INTEG (+Correct Task Construction Rate-Completion Rate,0)
Units: Tasks
The stock of correct tasks being constructed, derived from the difference between the correct task construction rate and the completion rate.

(16) Correct Tasks Completed Waiting Inspection= INTEG (Correct Completion Rate-Correct Task Validation Rate, 0)
Units: Tasks
The number of tasks that are completed correctly and waiting for inspection.

(17) Design Rate= Correct Completion Rate+Incorrect Completion Rate
Units: Tasks/Week

The rate at which designs are being completed, determined by the sum of correct completion rate and incorrect completion rate.

(18) Design Sharing=
0.1+STEP(Step Height CDS, Step Time CDS)+RAMP(Ramp Slope CDS, Ramp Start Time CDS , Ramp End Time CDS)
Units: dmnl
The total amount of time spent on sharing designs. Traditionally design teams meet three times (30%, 60%, 90% design stages) after conceptual design has been completed, to share design changes.

(19) Effect of Constructability and Design Sharing on Error Fraction=
Effect of Design Sharing on Error Fraction*Error Fraction Weight from Design Sharing + Effect of Constructability on Error Fraction*Error Fraction Weight from Constructability
Units: dmnl
The combined effect of constructability and design sharing on error fraction.

(20) Effect of Constructability on Error Fraction=
Lookup for Effect of Relative Constructability on Error Fraction(Relative Constructability)
Units: dmnl
Represents the impact that relative constructability has on error fraction.

(21) Effect of Design Sharing on Error Fraction= Lookup for Effect Of Relative Design Sharing on Error Fraction(Relative Design Sharing)
Units: dmnl
The effect design sharing on error fraction based on a predetermined distribution that represents the more you share designs the less errors fraction a design will have.

(22) Error Fraction Weight from Constructability= 0.78
Units: dmnl
A fixed value representing weight of constructability on the error fraction.

(23) Error Fraction Weight from Design Sharing= 0.22
Units: dmnl
The weighted amount of design sharing has on the error fraction, set to .22.

(24) FINAL TIME = 100
Units: Week
The final time for the simulation.

(25) Incorrect Completion Rate= MIN((Tasks Waiting To Be Worked/Time Standard)*Adjusted Error Fraction,Task Capacity*Adjusted Error Fraction)
Units: Tasks/Week

This is the incorrect completion rate which is the lowest of the task capacity times the adjusted error fraction or the tasks waiting to be worked divided by the standard amount of time it takes to complete a task.

(26) Incorrect Task Construction Rate=Validated Incorrect Tasks/Average Contracting Time
Units: Tasks/Week
The rate at which incorrect tasks get constructed; determined by the ratio of validated incorrect tasks and the average contracting time.

(27) Incorrect Task Validation Rate= (Incorrect Tasks Completed Waiting Inspection/Time to Inspect)*(1-Inspection Success Rate)
Units: Tasks/Week
The rate at which incorrect tasks are validated, determined by taking the ratio of incorrect tasks completed waiting inspect and time spent to inspect times the inspection success rate.

(28) Incorrect Tasks Being Constructed= INTEG (Incorrect Task Construction Rate-Incorrect Tasks From Construction,0)
Units: Tasks
The stock of incorrect tasks being constructed, determined by the difference of incorrect tasks construction rate and the incorrect tasks from construction.

(29) Incorrect Tasks Completed Waiting Inspection= INTEG (Incorrect Completion Rate-Incorrect Task Validation Rate-Incorrect Tasks Identified,0)
Units: Tasks
The number of incorrect tasks waiting to be validated. Determined by taking the incorrect completion rate less the incorrect task validation rate less the incorrect tasks identified.

(30) Incorrect Tasks Completion Rate= Incorrect Completion Rate
Units: Tasks/Week
This is the rate at which incorrect tasks are completed.

(31) Incorrect Tasks From Construction= Incorrect Tasks Being Constructed/Time to I identify Incorrect Task During Construction
Units: Tasks/Week
This is the rate at which incorrect tasks are constructed, determined by the ratio of incorrect tasks being constructed and the time to identify incorrect task during construction.

(32) Incorrect Tasks Identified=(Incorrect Tasks Completed Waiting Inspection/Time to Inspect)*Inspection Success Rate
Units: Tasks/Week

This is the rate at which incorrect tasks are identified. The rate is a ratio of the incorrect tasks completed waiting inspection and the time to inspect then multiplied by the inspection success rate.

(33) Initial Error Fraction= Lookup for Effect of Learning on Error Fraction(Total Tasks Learned From)
Units: dmnl
The initial amount of error fraction based on a learning rate that as you have more experience on a project your learning rate is increased.

(34) INITIAL TIME = 0
Units: Week
The initial time for the simulation.

(35) Inspection Rate= Correct Task Validation Rate + Incorrect Task Validation Rate + Incorrect Tasks Identified
Units: Tasks/Week
The rate at which tasks are being inspected, includes the sum of correct task validation rate, incorrect task validation rate and incorrect tasks identified.

(36) Inspection Success Rate=Lookup for Effect of Relative Constructability on Inspection Success Rate (Relative Constructability)
Units: dmnl
The rate at which inspections are conducted successfully, set by a look up table relating the effect of constructability on inspection success.

(37) Learning Rate=Correct Completion Rate + Incorrect Tasks From Construction + Incorrect Tasks Identified
Units: Tasks/Week
The rate a which A&E teams learn basked on the correct completion rate, incorrect tasks from construction and incorrect tasks identified.

(38) Lookup for Effect of Learning on Error Fraction([(0,0)-(1024,1)],(1,0.9),(2,0.72),(4,0.576),(8,0.46),(16,0.369),(32,0.295),(64,0.236),(128, 0.189),(256,0.151),(512,0.121),(1024,0.097))
Units: dmnl
As tasks learned from doubles, the error rate is reduced by 20%.

(39) Lookup for Effect of Relative Constructability on Error Fraction(
[(0,0)-(20,2)],(0,2),(0.5,1.3),(1,1),(2,0.7),(4,0.4),(8,0.3),(16,0.2))
Units: dmnl
Predetermined values that represent how constructability will impact error fraction.

(40) Lookup for Effect of Relative Constructability on Inspection Success Rate ([(0,0)-(10,1)],(0,0.07),(0.5,0.11),(1,0.2),(2,0.55),(4,0.82),(8,0.96))

Units: dmnl

(41) Lookup for Effect Of Relative Design Sharing on Error Fraction([(0,0)-(10,2)],(0,2),(0.5,1.2),(1,1),(2,0.7),(4,0.5),(8,0.3),(10,0.2))
Units: dmnl

(42) New Activity Rate= Correct Task Construction Rate + Incorrect Task Construction Rate
Units: Tasks/Week
The rate a which new activities are constructed, the sum of the correct task construction rate and the incorrect construction rate.

(43) Normal Constructability=0.25
Units: Hours/Week
This value represents the current amount to constructability A&E firms do with the project subcontractors or associates in the trade.

(44) Normal Design Sharing= 0.1
Units: dmnl
This value represents the amount of design sharing that A&E firms do through the evolution of a building design. Most A&E teams conduct standard meetings to update each other of design changes at 30%, 60%, 90% and design completion.

(45) Number of Projects= 1
Units: Projects
The number of projects a firm is working on.

(46) Project Complete= IF THEN ELSE(Tasks Constructed>=990, 1 , 0)
Units: dmnl
The project is defined to be finished when 99% of the work is done. The project finished switch shuts off the application and accounting of tasks constructed.

(47) Ramp End Time C= 0
Units: Weeks

(48) Ramp End Time CDS=0
Units: Weeks

(49) Ramp Slope C= 0
Units: dmnl

(50) Ramp Slope CDS= 0
Units: dmnl

(51) Ramp Start Time C= 0
Units: Weeks

(52) Ramp Start Time CDS= 0
Units: Weeks

(53) Relative Constructability= Constructability/Normal Constructability
Units: dmnl
The ratio of the amount of constructability a design team decides to conduct and the normal amount of constructability conducted by design teams.

(54) Relative Design Sharing= Design Sharing/Normal Design Sharing
Units: dmnl
The amount of relative design sharing is a ratio of the design sharing amount and the normal design sharing conducted by design teams.

(55) SAVEPER = TIME STEP
Units: Week [0,?]
The frequency with which output is stored.

(56) Step Height C2= 0
Units: dmnl

(57) Step Height CDS= 0.125
Units: dmnl

(58) Step Heigt C= 0
Units: dmnl

(59) Step Time C= 50
Units: Weeks

(60) Step Time C1= 70
Units: Weeks

(61) Step Time CDS= 0
Units: Weeks

(62) Task Capacity= 25
Units: Tasks/Week
Task Capacity is the product of the number of engineers and engineer productivity, set at 25.

(63) Tasks Constructed= INTEG (Completion Rate,0)
Units: Tasks
The total tasks that were constructed correctly determined by the completion rate.

(64) Tasks Waiting To Be Worked= INTEG (+Incorrect Tasks From Construction +Incorrect Tasks Identified-Correct Completion Rate-Incorrect Completion Rate, Number of Projects*Average Tasks per Project)
Units: Tasks
The stock of total tasks waiting to be worked. This valise is initially set to 1000. Once the simulation commences the model will account for all the incorrect tasks from construction, incorrect tasks identified less correct completion rate less the incorrect completion rate.

(65) Time Standard= 1
Units: Week

(66) TIME STEP = 0.03125
Units: Week [0,?]
The time step for the simulation.

(67) Time to Identify Incorrect Task During Construction= 2
Units: Week
On average, once construction of an incorrectly designed task begins, it takes 2 weeks to identify that the task is incorrect and needs to be redesigned.

(68) Time to Inspect= 2
Units: Weeks

(69) Total Activities= INTEG (New Activity Rate,0)
Units: Tasks
An activity is a group of tasks that make a complete product (i.e. interior electrical, plumbing, HVAC). The total activities are represented by the sum of the correct task construction rate and the incorrect construction rate.

(70) Total Cost from Activities= Average Cost Per Activity*Total Activities
Units: Dollars
The cost to complete one activity, which is the average cost per activity times the total activities.

(71) Total Cost From Design Iterations= Average Cost Per Design Iteration*Total Design Iterations
Units: Dollars
The total cost for design iteration on an activity including negative design iterations.

(72) Total Cost from Inspections= Average Cost Per Inspection*Total Inspections
Units: Dollars

(73) Total Design Iterations= INTEG (Design Rate,0)
Units: Tasks

The accumulation of total design iterations derived from the design rate.

(74) Total Inspections= INTEG (Inspection Rate, 0)
Units: Tasks
The total amount of inspections including incorrect tasks that were validated and need to be re-inspected after they are redesigned.

(75) Total Project Cost=Total Cost from Activities+Total Cost From Design Iterations+Total Cost from Inspections
Units: Dollars
The total cost of the project derived from the sum of the total cost from the activities, total cost from design iterations and total cost from inspections.

(76) Total Tasks Learned From= INTEG (Learning Rate,0)
Units: Tasks
The accumulation of tasks an A&E team learns from.

(77) Validated Correct Tasks= INTEG (+Correct Task Validation Rate-Correct Task Construction Rate,0)
Units: Tasks
The stock of correct tasks validated. Which is the difference between the correct tasks validation rate and the correct task construction rate.

(78) Validated Incorrect Tasks= INTEG (+Incorrect Task Validation Rate-Incorrect Task Construction Rate, 0)
Units: Tasks
The stock of validated incorrect tasks determined by the difference between the I ncorrect task validation rate and the incorrect task construction rate.

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